The Flash Crash: Trading Aggressiveness, Liquidity Supply, and the Impact of Intermarket Sweep Orders

Sugato Chakravarty
Purdue University
West Lafayette, IN 47906
sugato@purdue.edu, 765-494-8296

James Upson*
University of Texas, El Paso
College of Business , El Paso, TX 79968
jeupson@utep.edu, 915-747-7758

Robert Wood
University of Memphis
rawood@pobox.com, 801-796-6401

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*Contact Author.

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Abstract:

On 6 May 2010, the stock market experienced a large price decline and recovery collectively known as the Flash Crash. We investigate the contribution of trading aggressiveness to the Flash Crash event. We find that trading aggressiveness was significantly higher on the day of the Flash Crash, as proxied by the use of Intermarket Sweep Orders (ISO). ISOs have been found to be primarily used by informed institutional traders and are allowed to trade through the best prices in the market. We show that the information content of ISO trades on the day of the Flash Crash was higher than Non-Sweep Order (NSO) trades, as measured by the information shares method of Hasbrouck (1995). In addition, the ability of ISO trades to trade through the best prices was used significantly more on the day of the Flash Crash, particularly in the 30 minute period just prior to the crash. Our results indicate that ISO volume imbalance has a significant impact on market returns while the NSO volume imbalance was insignificant. As markets became thin, traders shifted to ISO trades in order to capture counter party depth. We recommend the potential initiation of ISO labeled trading usage halt during periods of high market wide volatility.

On the afternoon of May 6th, 2010, the U.S. stock markets suffered one of the most severe price drops in history, with the DOW dropping almost 1,000 points in a matter of minutes, only to recover a significant portion of the loss later in the same day. This price drop has been labeled as the 'Flash Crash' by the popular press. Such a large and rapid drop in prices and equally rapid subsequent recovery raises serious questions about the stability and structure of US equity markets. In particular, a WSJ.com blog, dated May 7, 2010, sported the suggestive title: "*Accenture's Flash Crash: What's an Intermarket Sweep Order*?"[1] The gist of the article provides anecdotal evidence to suggest that a relatively new kind of order, entitled the Intermarket Sweep Order (henceforth, ISO), may have played a significant role in the perpetration of the crash.[2] The goal of the current paper is to investigate the veracity of this claim.[3]

Specifically, we focus our analysis on three basic questions surrounding the Flash Crash. First, we wish to see if the use of ISO labeled trades was significantly larger on the day of the Flash Crash and if these trades represented informed trading. Second, we examine whether the "trade through" provisions of ISO trades were used to a higher degree during the period of the Flash Crash. This is relevant because if we were to find evidence that suggested a greater number of trade throughs during this period, it would provide direct evidence of the fact that ISOs may have helped destabilize the market. Third, we investigate if ISO trades have a disproportionate impact on market and stock level returns. We contrast the impact of ISO volume with Non-Sweep Orders (henceforth, NSO) on the day of the Flash Crash.

Using a sample of stocks that comprise the S&P 500 we find that the ISO volume is significantly higher on the day of the Flash Crash, based on exchange executed trades and our reference period of the first three trading days in the month of May over the same stocks. For instance, in the thirty minutes prior

[1] This can be found at http://blogs.wsj.com/marketbeat/2010/05/07/accentures-flash-crash-whats-an-intermarket-sweep-order/.

[2] An intermarket sweep order (ISO) is a limit order that automatically executes in a designated market center even if another market center is publishing a better quotation. An investor submitting an ISO must satisfy order-protection rules by concurrently submitting orders to the markets with better prices. From a regulatory standpoint, the ISO came into existence in the wake of the adoption of Regulation National Market System (Reg. NMS). Specifically, Rule 611 of Reg NMS, known as the Order Protection Rule, created enforceable penalties if one market center executed a trade at an inferior price while another market center was posting a better price. However, there was an important exemption to the Order Protection Rule specified in paragraphs (b)(5) and (b)(6) of the rule: the Intermarket Sweep Order (ISO). Specifically, ISO trades were allowed to trade through the best posted prices in the market but not breach Rule 611.

[3] The properties of ISO trades are investigated in Chakravarty, Jain, Upson and Wood (2011).

to the Flash Crash, we find a 7% increase in ISO volume over our base period even thought ISO volume was high over the whole day.

To evaluate the information content of ISO trades on the day of the Flash Crash, we adopt the information shares method of Hasbrouck (1995). We divide each trading day into 13 thirty-minute periods. For the majority of the Flash Crash day, the information share of ISO volume is well over 50% and is significantly higher than the base period. We also evaluate the information ratio of ISO trades defined as the point estimate of the information share for ISO trades divided by the percentage of ISO volume. An information ratio of 1.0 (> 1.0) means the information content of the trades equals (exceeds) its fair volume contribution. Our results show, with the exception of the 30 minute period following the Flash Crash, the information ratio of ISO trades is significantly greater than 1.0 in the base period and on the Flash Crash day. These findings imply that traders using ISO labeled trades are informed and were, in fact, driving the market during the day of the Flash Crash. In related work, Easley, Lopez de Prado, and O'Hara (2010) also find that order flow was highly informed prior to the Flash Crash based on the *Volume-Synchronized Probability of informed Trading* (VPIN) method. Their results indicate that order flow was 'toxic' in the sense that sell volume was larger than buy volume. We find that it was the ISO trades that were a major source of this toxic order flow.

One of the key advantages of ISO trades is that they can be used to trade against posted liquidity that is outside of the best prices prevailing in the market. However, if an ISO trader wishes to access this liquidity, she must submit ISO trades simultaneously to all market centers posting better prices. In other words, every ISO trade that occurs outside of the best prices must be linked to a series of ISO trades that match the size of posted liquidity in all other markets posting better prices. Clearly, if traders believe that prices will move well outside the current levels, using ISO trades to consume liquidity at current prices will be profitable. Our findings show that significantly more ISO initiated trade throughs occurred on the day of the Flash Crash with each trade through (by the Order Protection Rule, Rule 611 of Reg NMS) being linked to a series of ISO trades taking all posted top-of-the-book depth from all market centers posting better prices. Faced with a large increase in aggressive informed trading and a high degree of potential information asymmetry, liquidity supply dropped.[4]

But how does a withdrawal of liquidity impact the choice between aggressive ISO trades and less aggressive NSO trades? Our regression results indicate that ISO use was positively serially correlated, with increases in ISO use followed by additional increases in ISO use and, as the market became less liquid, traders' use of the ISO trade type increased. This result highlights a structural issue with the current market that is the focus of our current research. Namely, during normal market operations, ISO trades are a productive, and valuable, tool for the market participants. By the same token, however, they can also critically destabilize markets during periods of high market wide volatility or even during periods of panic trading. A policy recommendation emanating from the current analysis is to introduce a mechanism to temporarily halt ISO labeled trading when market volatility reaches a predetermined high water mark level. We also assess the relative impact of ISO and NSO volume imbalance on market and stock level returns. Our findings indicate that contemporaneous volume imbalance of ISO trades shows a significant positive correlation with returns but that the NSO volume imbalance is insignificant in comparison.

The balance of the paper proceeds as follows. In section 1.0 we review best pricing provision of Reg NMS to set the basis for our research methods. In section 2 we briefly review our data. Section 3 shows our results and Section 4 contains our policy recommendations. We conclude in Section 5.

1. Regulation NMS overview

The Order Protection Rule of Reg NMS, Rule 611, specifies that an exchange cannot execute a trade when another market center is posting a better price. The exchange that received the trade must re-route the order to the market center(s) that is posting the better price. However, the Securities and Exchange Commission (SEC) recognized that, in modern markets, quotes within a market center could

[4] Kirilenko, Kyle, Samadi, and Tuzun (2010) investigate the role of HFTs in the E-mini S&P 500 futures market and find that while the HFTs did not cause the Flash Crash, they did exacerbate the volatility of the market.

change significantly faster than price updates could be transmitted to other market centers for the evaluation of a market wide best price. The SEC therefore adopted the 'Flicker Quotes Exception'.[5] This exception states that a market center can only claim a trade through violation if the trade occurred outside of the least aggressive ask (bid) price over the previous one (1) second of trading for a buy (sell) order on the market center claiming the trade through. For all market centers, the Flicker Quote Exception implicitly defines the reference price for the evaluation of a trade through as the least aggressive National Best Bid and Offer (NBBO) ask and bid prices over the previous one (1) second of trading. In this paper we define the least aggressive NBBO ask and bid prices over the previous one (1) second as the Flicker Ask (Bid) Price taken together as the Flicker Price. Any liquidity offered that is at, or inside of, the Flicker Price is available for immediate execution, regardless of the order type used, without breaching the Order Protection Rule. Posted liquidity that is outside of the Flicker Price, by rule, can only be accessed using an ISO trade but, once accessed, the ISO trade initiator must also route trades to all markets posting quotes inside the flicker quote, on the same side of the market, with a total trade volume that matches the posted top of book liquidity for each better priced exchange. We define the event when an ISO trade is found to trade through the Flicker Ask (Bid) as a 'market depth sweep', indicating that the ISO trade through will be coupled with a series of ISO trades removing all posted top-of-the-book liquidity quoted at better prices than the Flicker Ask (Bid). ISO trades can and are used to access liquidity at NBBO and Flicker Prices, without initiating a market depth sweep and we include this definition to differentiate the two different applications of ISO trades. The Flicker Price, as defined in this paper, plays a key role in the analysis of trade aggressiveness during the Flash Crash.[6]

[5] Historically 'flickering quotes' refers to a market state where one market center rapidly flashes different quotes to signal additional interest at prices other than the top of the book. The SEC adapted the term 'Flicker Quote' when promulgating the Order Protection Rule, and we adopt the SEC terminology. We apologize for any confusion related to the change in definition of Flicker Quote. SEC release 34-51808 discusses the Flicker Quote Exception on page 152.
[6] The impact of the Flicker Quote Exemption is explored in McInish and Upson (2011)

2. Sample and data

Our sample consists of all stocks that are part of the S&P 500. We selected this sample for two reasons. First, the Flash Crash represents a market wide event, and the S&P 500 provides a broad representation of the pulse of the overall market. Second, the Flash Crash has been linked to futures trading in E-mini S&P 500 futures and this sample allows for the impact of arbitrage trading between the futures contract and the underlying equities (see, for instance, Easley, Lopez de Prado, and O'Hara, 2011; Kirilenko, Kyle, Samadi, Tuzun, 2011).

Our dataset comprises the Daily Trade and Quote (DTAQ) data from the NYSE. This dataset contains timestamps to the millisecond, for all trades and quotes from all exchanges, and the exchange calculated National Best Bid and Offer (NBBO). The DTAQ database is similar to the monthly Trade and Quote (TAQ) database regularly used in microstructure research but has additional condition codes associated with trades and quotes. Our dataset covers the month of May, 2010. Our reference period comprises the three days prior to the Flash Crash -- the first three trading days of May. Only exchange executed trades are included in the bulk of our analysis.[7]

3. Results

3.1 Intraday volume and ISO use.

First, we wish to establish the timing and scope of the Flash Crash. We begin this effort by investigating the trading volume on the day of the crash. Figure 1 presents a minute-by-minute median

[7] The DTAQ database also allows for the identification of trades that are reported though the Trade Reporting Facility (TRF) of a market center. TRF trades are executed off exchange, such as in a dark pool or internalized order flow, but reported to the consolidated tape through the TRF of an exchange. For the majority of our analysis, we exclude TRF trades for several reasons. First, the quote data in the DTAQ database is only based on exchange level quotes. Therefore, the liquidity provision at off exchange trade venues is unobservable. Without the liquidity provision, we cannot assess the impact of TRF trades on the overall market depth. Second, TRF trades represent matched supply and demand and therefore do not directly impact exchange level quote based liquidity. For example, the dark pool and internalized order flow would first match buy and sell orders, with the unmatched residual being routed to the exchange level for execution. It is these exchange level trades that would impact the market liquidity. Third, we will offer evidence that TRF order flow has low information content and marginal impact on the price discovery process. Based on these findings we feel that TRF trades had minimal impact on the exchange level liquidity conditions that existed on the day of the Flash Crash. This conclusion is further supported by the SEC/CFTC report, dated 20 September 2010, regarding internalization and TRF trades on page 57.

trading volume for our sample stocks both for the base period and over the day of the crash. This order flow is based only on exchange executed trades. As noted before, our reference period is the three trading days before the day of the Flash Crash. For each minute of the trading day, we sum the trading volume for the base and sample periods. To account for the skewness in the distribution of the trading volume, we plot the median, rather than the mean trading volume for our sample. For reference, we also plot the equally weighted average return of the sample based on the opening price of each stock on the day of the Flash Crash. In the first 100 minutes of trading, there is little significant deviation between the base period and the day of the Flash Crash. After the 100 minute mark, median trading volume begins to periodically spike over the base period reference levels, but also periodically returns to base levels. At the 260 minute mark (1:50 pm EST), volume begins to rise rapidly and continues to increase until just before the low point of the market.[8] The after this point, volume drops, but remains well over the value of the base period for the remainder of the trading day. Note that the rapid increase in volume occurs well before the 75,000 mini-E contract trade that occurred at 2:32 pm (minute 302) and identified in the Joint SEC/CFTC Flash Crash report of 30 September 2010, and by Kirilenko *et al* (2011).

Figure 2 shows the time weighted median total quoted depth, in round lots, on the day of the Flash Crash. For each minute of the trading day we time weight the total depth, ask plus bid, which is posted for execution without violation of the Order Protection Rule, Rule 611, of Reg NMS. Specifically, any depth with a quoted price that is at or inside the Flicker Ask Price and Flicker Bid Price is included in the evaluation. Starting from early in the trading day posted depths are lower than the base period. Concurrently with the increase in trading volumes, quoted depths deviate dramatically from the base line period and remain below reference levels for the remainder of the trading day.

While acknowledging the excellent work done in the SEC/CFTC report on the Flash Crash, we feel that we would be remiss if we didn't point out the fact that one significant issue missing from the report is the market impact of ISO trades on the day of the Flash Crash. Figure 3 shows the percentage of

[8] This rise in volume occurs eight minutes after press reports of Greek Police charging protestors in Athens. See for example Agence France Presse report at 6:42 GMT (1:42 pm EST) on LexisNexis.

exchange executed volume from ISO trades compared to the based period. The figure clearly indicates that ISO use on the day of the Flash Crash was high, starting early in the trading day. In addition, relative to the base period, as the day of the Flash Crash progressed, ISO use increased through the period of the Flash Crash. Only after the prices had recovered, does ISO use return to based levels. While our graphic analysis helps characterize the market conditions on the day of the Flash Crash, we next turn to a more formal analysis of the impact of ISO trades on market conditions.

3.2 Information content of ISO trades

We start by formally showing that the level of ISO use on the day of the Flash Crash is statistically higher than the base period. ISO and NSO trades bifurcate the trade types recorded in the DTAQ database, i.e. the percent of NSO volume is equal to 100 minus the percent of ISO volume. Table 1 shows the results of this analysis. The trading day is divided into 13 thirty minute intraday segments. For each stock segment we sum the volume traded with ISO orders and divide the ISO volume by the total volume traded for the stock. The average percentage of ISO volume is then calculated for each segment of the day. Mean and median percentage use of ISOs is shown. For reference, segment 10, ending with minute 300 (2:30 pm EST) represents the period prior to the Flash Crash and segment 11 is the 30 minute period of the Flash Crash. With the exception of period 12 (from 3:00 to 3:30 pm EST), ISO volume is significantly higher than the base period. In the period prior to the Flash Crash, the average ISO volume is about 7% higher per stock than the based period, representing a significant portion of the stock dollar volume traded on the S&P 500 stocks. The level of ISO volume, relative to the based period, increased during the period of the Flash Crash. We next show that the high level of ISO use disproportionately impacted the price volatility of the market.

Rational liquidity suppliers, faced with a large increase in volume, and informed volume in particular, may choose to withdraw from the market rather than actively trade with those better informed about the future price movements of stocks. The analysis is based only on exchange executed trades.[9] To assess the information quality of the ISO order flow we adopt the information shares method of Hasbrouck (1995). This method uses a vector autoregressive error correction model to decompose the random walk contribution from each price input into the efficient price evolution process.

Functionally, we form two price channels, one for ISO trades and one for NSO trades. We use the last trade price of each trade type in each second.[10] The use of trade prices follows Hasbrouck (2003), Anand and Chakravarty (2007), Chakravarty, Gulen, and Mayhew (2004), and Goldstein, Shkilko, Van Ness, and Van Ness (2008). Our trade prices can vary across markets as well as within markets, following the technique applied in Hasbrouck (1995). Unless the resulting variance co-variance metric is diagonal, the information share estimate for each trade type is not identified. As a point estimate we take the average of the upper and lower bound information share values. We again divide the trading day into 13 thirty minute segments and evaluate the information share for each stock segment.

Hasbrouck (1995) finds that the price discovery process is under represented on regional stock exchanges because the information share of these exchanges is well below the traded volume of shares executed by these exchanges. When evaluating the information quality the ISO order flow, the information share of ISO order flow must be conditioned by the proportion of volume attributable to this trade type. Accordingly, we define the information ratio (*InfoRatio*) as:

$$InfoRatio_{i,t} = \frac{ISO\,InfoShare_{i,t}}{ISO\,VolShare_{i,t}} \quad (1)$$

Where t is the period of the day and i is the stock in the sample. $ISO\ InfoShare_{i,t}$ is the point estimate of the information share for ISO trades and $ISO\ VolShare_{i,t}$ is the percentage of ISO volume over the period t. An information ratio greater than 1.0 (below 1.0) indicates the ISO trades carry information greater

[9] In section 3.7 we re-examine the information shares results using all trades (exchange executed and TRF) in the DTAQ database. The results are stronger and our conclusions remain unchanged.
[10] Although the DTAQ database has time stamps to the millisecond, the number of observations generated for the method is computationally prohibitive.

than (less than) that implied by its volume. The results of the information share analysis are shown in Table 2.

For each stock day segment in the based period we find the average information share. We then conduct a paired t-test for each stock period differencing the ISO information share on the Flash Crash day from the average of the base period. For the majority of the periods on the day of the Flash Crash, the information share if ISO trades is greater than over the corresponding base periods. For example, in period 10, the information share of ISO trades is 0.514 compared to the base period of 0.497 and is significantly different at better than the 5% level. However, as noted earlier, this increase in information share could simply reflect the higher ISO volume found on the Flash Crash Day. The critical finding is that the information ratio for ISO trades is significantly different from 1.0 for all periods of the trading day except period 12. In period 10, just prior to the Flash Crash, the information ratio of ISO trades is 1.049 and significantly greater than 1.0 at better than the 1% level. This indicates that ISO trades contributed an additional 5% to the price variance above and beyond the volume level of ISO trades.

We also test if the information ratio of the ISO trades on the day of the Flash Crash is statistically different than the information ratio in the corresponding base period. Our results indicate, particularly during the later period of the trading day, that there is a decrease in the information quality of ISO order flow. Starting in period 8, the information ratio for ISO trades is significantly smaller than the based period for the remainder of the Flash Crash Day. In period 8 it is 1.090 versus 1.206 in the based period. For the majority of the morning periods we find no statistical difference between the information ratios for the Flash Crash day and the based period. We interpret this result as follows. During the morning on the day of the Flash Crash, informed traders aggressively took liquidity from the market using ISO trades. As the day progressed, liquidity, as measured by quoted depths, decreased from all of the aggressive trading. Pure liquidity traders, faced with thinning markets, migrate to aggressive ISO trades, with the result that the information content of ISO order flow decreases. In later sections, we present further evidence to support this interpretation.

3.3 Trade through analysis

In this section we analyze the level of trade throughs of ISO trades. An important advantage of ISO trades is that they can access posted liquidity outside of the Flicker Price as long as concurrent with the outside trade, sufficient order volume is directed to markets posting better prices to consume the top-of- the- book posted liquidity. Critical to our analysis is the proper alignment between trades and NBBO quotes that are in force at the time of the trade. We align trades and NBBO quotes based on the following process, first proposed by McInish and Upson (2011). The vast majority of trades in today's markets are executed in the matching engines of each market center without human involvement. Co-located computer systems, low latency intermarket communication links, and sophisticated trading algorithms indicate that order flow will be routed to the market center(s) posting the best price or NBBO. We therefore assume that the most correct alignment between trades and NBBO quotes is the time lag that maximizes the percentage of trades executing at NBBO prices. We test quote lags from 0 to 350 milliseconds in 25 millisecond (0.025 second) increments. Recognizing that lag times could possible vary over the trading day, we evaluate the optimal lag time for each 30 minute period of the day. For each stock day period there is a unique lag time applied to the NBBO quote that results in the maximum number of trades executing at the NBBO quote. For reference, Figure 4 displays the global average of exchange executed trades at the NBBO quote, inside the NBBO quote, and outside the NBBO quote as a function of the lag time between the NBBO quote time stamp and the trade time stamp.

Table 3 reports the average lag time for each period of the trading day, separately for the Flash Crash day and the base period. We also report the percentage of trades that execute at or inside of the NBBO quote for all exchange executed trades, ISO trades, and NSO trades. Overall, the lag times and percentage of trades at the NBBO quote are comparable between the base period and the Flash Crash Day. A higher percentage of NSO trades execute at the NBBO quote than ISO trades, supporting our assertion that ISO trades are more aggressive than NSO trades, taking liquidity at inferior prices to the NBBO. As noted in section 1 of this paper, a trade outside of the NBBO quote is not necessarily a trade through violation of the Order Protection Rule. The trade must be outside of the Flicker Price, which is the least aggressive NBBO ask and bid over the previous one second of trading, for the trade to be considered a trade through.

Based on the trade alignment, we next proceed to the trade through analysis. A trade through is defined is a trade, executed at a price strictly over the Flicker Ask Price or under the Flicker bid price. We first apply the appropriate time lag to the NBBO quote to find the NBBO quote in force at the time of the trade. Next we look back over the previous one second of NBBO quotes and find the least aggressive NBBO ask and bid prices to identify the Flicker Ask and Flicker Bid reference prices for the identification of a trade through.

Before proceeding, we caution the reader regarding the veracity of the trade through results from the period of the Flash Crash, period 11, through the end of the trading day, for two reasons. First, the NYSE recalled the initial issue of the DTAQ database on the day of the Flash Crash in order to perform data error checks and later issued a new corrected version of the database. It is this second database that we use in our analysis. The distribution notes of the reissued database indicate that one of the main reasons for the recall was errors in the time stamps of trades and quotes over the period of the Flash Crash. The time stamp issue is also corroborated in the SEC/CTFC report on page 77, indicating that quote reporting delays of 5 seconds, on average, occurred between 2:45 pm and 2:50 pm on the day of the Flash Crash. It is possible, if not likely, that during the real time Flash Crash event, exchanges executed trades at prices that, based on the delayed reporting of NBBO quotes, were not trade throughs as per the initial database, but when checked against the corrected database *ex post*, were in fact trade throughs. Second, several market centers issued a declaration of ‘Self Help’ against NYSE ARCA. The Order Protection Rule allows one market center to declare ‘Self Help’ against another market center when the offending market center does not respond to orders from the sending market center within one (1) second. After the declaration of ‘Self Help’, the declaring market center can trade through better prices on the offending exchange without violation of the Order Protection Rule. This issue is discussed on page 75 of the SEC/CTFC report. The ‘Self Help’ declarations occurred roughly between 2:35 pm and 3:02 pm. The DTAQ database does not contain ‘Self Help’ declarations and so we are unable to directly control for this issue. Although the last three time segments of the analysis are highly suspect, we find no documentation from the DTAQ database or the SEC/CTFC report that latency and reporting issues occurred prior to 2:30 pm EST, corresponding to segment 10 and prior in our results. Since the focus of our analysis is on the market conditions leading onto the Flash Crash, and can find no contrary indications that the database is not reliable through 2:30 pm, we believe that our results can be confidently interpreted for the first 10 thirty minute trading periods of the Flash Crash day.

The trade through results are shown in Table 4. The table presents the mean (Panel A) and median (Panel B) number of trade throughs for ISO and NSO trades that are over the Flicker Ask and Under the Flicker Bid prices. For Panel A, we first calculate the average number of trade throughs for the base period and then conduct paired t-tests for each stock segment. In Panel B, we compare the median values of trade throughs on the Flash Crash day, and the base period, based on a Wilcoxon Rank Sum test. NSO trade throughs are included in our analysis as a check on the Trade/Quote alignment. By rule, NSO trades should not trade through the Flicker Price, although some of these NSO trade throughs could, in fact, be actual trade throughs. We feel that the majority of NSO trade throughs are the result of a slight misalignment between the trades and quotes. Since ISO and NSO trades occur contemporaneously, we believe that a reasonable assumption is that the alignment error is consistent for ISO and NSO trades. Our best estimate, given the limitations of the database, of the number of ISO trade throughs is therefore the difference between ISO and NSO trade throughs. For clarity, we limit our discussion to the tabled values of ISO trade throughs rather than the difference (ISO-NSO) trade through value.

The results indicate that during the first two periods of the Flash Crash day, trade throughs of ISO orders are either similar to the base period or significantly reduced. After this, the ISO trade throughs become significantly larger than the base period on both the ask and the bid side of the market, for most of the segments. We wish to emphasize that, by the Order Protection Rule, each trade representing an ISO trade through should be linked to a series of trades, with sufficient volume, to take out the top of book quoted depth from all market centers at better prices than the trade through price. When these market sweeps of depth occur, both liquidity demanders and liquidity suppliers will observe at least one price point (and possibly several price points) removed from the market in a matter of milliseconds. In period 10, the level of ISO trade throughs increases three folds on both the ask and bid side of the market. When the market has abnormally low liquidity supply and abnormally high liquidity demand, market depth sweep orders are used to quickly remove liquidity from a fast thinning limit order book.

3.4 Market depth

In Table 5 we compare the liquidity supply environment between the day of the Flash Crash and the base period. We report the mean time weighted number of round lots available for immediate execution, without violation of the Order Protection Rule. In other words, all depth posted at prices at, or inside, the Flicker Price is included in the market depth. To evaluate the stability of market depth, we also report the standard deviation. We interpret a higher standard deviation of depth as a less stable liquidity environment. Table 5 also shows the average and standard deviations of market breadth. Breadth is defined at the time weighed number of market centers posting prices at or inside the Flicker Price. A higher level of breadth, i.e. more market centers posting liquidity, implies that liquidity demanders are better able to parallel process demand through multiple trading channels, obtaining faster executions. Chakravarty *et al* (2011), show that as markets narrow (Breadth decreases) ISO trade use increases.

Consistent with the implications of Figure 2, we find that both ask and bid quoted depth are lower on the day of the Flash Crash than in the base period after the first two periods of the day. In addition, for a number of periods, standard deviations of depth are higher on the day of the Flash Crash. Our conclusion is that not only were markets thin with regard to liquidity supply, but that the reliability of the liquidity supply was also lower. Our breadth results also indicate that markets are narrower on the day of the Flash Crash, with a higher standard deviation in many of the periods. Our results are consistent with the SEC/CFTC report and are included here to add context for our next analysis.

3.5 ISO use regression results

It appears as though on the morning of the Flash Crash day, informed traders aggressively entered the market using ISO trades to complete transactions. Supporting this contention is the observation that ISO use increased significantly over the first seven periods of the trading day. By the same token, however, the information ratio, with the exception of two periods, remained statistically indifferent from the base period. Our interpretation is that the higher ISO use carried the same information level as typical ISO trades during the morning and mid day periods of the Flash Crash day. However, the aggressive use of ISO trades, and the increased use of market depth sweeps, began to thin the market of posted liquidity. As a result, liquidity traders, or their algorithms, shifted to the more aggressive ISO trades to fill orders. To offer support for our contention, we estimate the following regression:

$$\Delta\%ISO_{i,t} = \alpha + \sum_{k=1}^{2} \beta_k \Delta\%ISO_{i,t-k} + \beta_3 \Delta\%Dpth_{i,t} + \beta_4 Dx + \beta_5 LnMcap_i + \varepsilon_{i,t} \qquad (2)$$

We first calculate the average percent of ISO volume and depth for each minute of the trading day in the base period and on the day of the Flash Crash -- 390 minutes for the base and 390 minutes on the day of the Flash Crash.[11] Next, we take the difference of ISO volume and depth. $\Delta\%ISO$ represents the difference in the percentage of ISO volume, $\%ISO_{Flsh}$-$\%ISO_{Base}$. $\Delta\%Dpth$ represents the percentage change in total depth, $(Dpth_{Flsh}-Dpth_{Base})/ Dpth_{Base}$. Dx is a dummy variable that is 1 on or after minute 302 (2:32 pm EST) on the day of the Flash Crash and zero otherwise. 2:32 pm is the time that a 75,000 mini-E contract sale order was initiated. We run the regression at the market level, aggregating data for the sample, as a cross sectional regression, and at the stock level. In the cross sectional regression, we include *LnMcap*, the natural log of market capitalization as a cross sectional control. Two lag level of $\Delta\%ISO$ are included in the regression.

The regression results are shown in Table 6. For all three regression models, the coefficients of the lagged values of $\Delta\%ISO$ are both positive and significant. This indicates that increases in ISO use on

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[11] On the day of the Flash Crash for the stock level and cross sectional regression, the average is equal to the value for each minute of trading. On the market level regression, the average represents the mean of all stocks in the sample.

the day of the Flash Crash tended to be followed by additional increases in ISO use, relative to the base period. More succinctly, the result indicates that the intensity of aggressive ISO trading increased, relative to expectation, as the Flash Crash day progressed. The coefficient of our contemporaneous depth variable is negative and significant for all three regression methods. While correlation does not indicate causality, the result is consistent with our belief that liquidity traders shifted to ISO type trades to fill orders in a timely fashion. The coefficient of the dummy variable is negative and significant in each of the regression specifications. This is consistent with the results of Figure 3, which shows that after the Flash Crash recovery, ISO use returned to baseline levels for a period of roughly 30 minutes. There are a number of potential reasons for the pause in ISO use after the recovery, but we choose to abstain from speculating on the cause of this decline. As a final comment, we note that in the cross sectional regression, the coefficient of the firm size control variable is both positive and significant at better than the 1% level. This indicates that the increase in ISO use tended to focus on the largest firms in our sample.

3.6 Volume imbalance

Up to this point, we have provided evidence showing that on the day of the Flash Crash there is a significant increase in the use of ISO orders to capture counter party depth, that ISO order flow had a disproportionate effect, relative to ISO volume, on the price variance, that the ISO trade through provision for a market depth sweep was exercised significantly more, and that the increase in aggressive ISO trading is to some extent dependent on decreased market depth. We now look at the impact of ISO volume order imbalance, relative to NSO volume order imbalance, and total volume order imbalance. We first characterize the magnitudes of order imbalance over the base period and the day of the Flash Crash. Volume order imbalance is defined at *100x(BuyVol-SelVol)/(BuyVol+SelVol)*, Where *BuyVol* and *SelVol* is for ISO or NSO trades. Trade inference is based on the Lee and Ready (1991) algorithm against the in-force NBBO quote based on the stock day lag identified in the Trade/Quote alignment procedure.

Volume order imbalance results are shown in Table 7. For each 30 minute period of the trading day we calculate the volume imbalance for each stock. We then average and report the volume imbalance in the table for the Flash Day and base period. We focus our discussion on the Flash day results. With the exception of the first period, NSO volume imbalance is negative for the balance of the day. ISO volume imbalance, however, was positive for several of morning periods. In periods 4, 5, and 6, ISO traders were substantially net buyers in the market even while NSO traders were substantially net sellers. However, market returns over this period were, in fact, increasing. Although anecdotal in nature, this observation raises an interesting conjecture. Namely, that ISO volume imbalance may have been driving the return generating process. We formally test this conjecture using regression analysis.

The impact of volume imbalance on market returns has been the focus of significant efforts in finance research. Our analysis of the impact of ISO volume imbalance follows the work of Chorida and Subrahmanyam (2004) and Chorida, Roll, and Subrahmanyam (2000). We estimate the following two regressions:

$$Rtrn_{i,t} = \alpha + \sum_{k=1}^{n} Rtrn_{i,t-k} + \sum_{k=0}^{j} Ibal_{i,t-k} + \sum_{k=0}^{m} Nbal_{i,t-k} + Flsh_t + \varepsilon_{i,t} \tag{3}$$

and

$$Rtrn_{i,t} = \alpha + \sum_{k=1}^{n} Rtrn_{i,t-k} + \sum_{k=0}^{h} Tbal_{i,t-k} + Flsh_t + \varepsilon_{i,t} \tag{4}$$

Where *Rtrn* is the NBBO quote midpoint return for period *t*, *Ibal* is the volume imbalance ISO trades, *Nbal* is the NSO volume imbalance, *Tbal* is the total volume imbalance, and *Flsh* is a dummy variable that is 1 if the period is after the 300 minute mark on the day of the Flash Crash and zero otherwise. We estimate each equation as a market wide regression and as a fixed effects regression. In addition, aggregation is based on two time increments, five (5) and ten (10) minutes. Lagged values of *Rtrn*, *Ibal*, *Nbal*, and *Tbal* are also included to minimize correlation in the error term and can differ, in the number of lags, by equation. Market returns are estimated by evaluating the period NBBO returns for each stock and then averaging. When estimated at the stock level, stock returns are market adjusted based on the equally weighted return of the sample. The results are shown in Table 8.

Panel A of Table 8 shows the market level results of the regression. For both aggregation periods, the coefficient of *Ibal* is positive and significant while the coefficients for *Nbal* are insignificant. The *Tbal* coefficient is significant only on the five (5) minute aggregation regression. We interpret the market wide results as follows. Order flow has two component impacts on prices, an information component and an inventory component. The information component is proxied by the ISO volume imbalance while the inventory component is proxied by the total volume imbalance. When both components are in alignment, such as when ISO volume imbalance is negative (positive) and total volume imbalance is negative (positive) the price reaction will be large, but when ISO and total volume imbalance are in conflict, price reactions will be small. After period 7, in Table 7, both ISO and NSO volume imbalance turned negative and while the level of imbalance was comparable to the base period, the magnitude of the imbalance in terms of shares was large. Panel B of Table 8 shows the cross sectional fixed effects regression results. The coefficient for *Nbal* is insignificant in both aggregation groups. In the five (5) minute aggregation group, the coefficient of *Ibal* is positive and significant. However, at the ten (10) minute aggregation, the *Ibal* coefficient is insignificant. *Tbal* is only significant in the five (5) minute aggregation regression, but with a negative sign and only at the 10% level.

Our regression results indicate that contemporaneous ISO order imbalance has a significant impact on the return generating process, while contemporaneous NSO order imbalance has little impact. Again, our results are consistent with the notion that ISO trades had a disproportionately large impact on market liquidity and returns on the day of the Flash Crash.

3.7 Robustness test

Our analysis to this point has only included exchange executed trades, with TRF trades excluded from the analysis. We dropped TRF trades from the analysis because our intuition is that they have little exchange level market impact. In this section we relax this constraint and re-examine the information share and return tables to substantiate our choice to drop TRF trades. Table 9 shows the results of the information share analysis with all trades included. The information share of ISO trades remains unchanged, at least to the three places reported, compared to the information share calculations when TRF trades are excluded. The information ratio however increases substantially. Our conclusion is that TRF volume has little impact on exchange level price volatility. These results support our restriction of TRF trades from the majority of the analysis.

Table 10 shows the volume imbalance regression results. The conclusions remain unchanged with no statistically significant sign reversals. Since many off exchange trading venues 'free ride' on market prices and convey little information to the market, the inclusion of TRF trades is likely to add more noise than explanatory power. Overall, our robustness tests indicate that the exclusion of TRF trades does not impact our results or conclusions.

4.0 Recommendations

Our analysis indicates that the ISO trade exemption to the Order Protection Rule represents a structural flaw in the market that can lead to instability when markets are stressed. We ask a simple question: under what market conditions would the ISO market depth sweep capabilities most likely be applied? Clearly, if markets are very liquid, market depth sweeps make little sense. It is only when liquidity is thin and markets are under stress that the potential costs of a market depth sweep are outweighed by the benefits of quickly removing large amounts of depth from the market. Hence, when markets are least able to accommodate aggressive trading is precisely when the ISO market depth sweep capabilities are most likely to be adopted.

In addition, recent studies such as Chakravarty *et al*, 2011, indicate that ISO order flow has higher information content than NSO order flow. A result confirmed in this analysis. Major market participants will likely understand the higher information content of ISO order flow and react accordingly. However, if markets become thin, liquidity traders will naturally migrate to the more aggressive ISO trade type to fill orders. Ironically, uninformed liquidity traders will end up hiding with informed traders in the ISO order flow, complicating the signal that suppliers of liquidity observe. We are not claiming that ISO trades created the Flash Crash -- there is likely multiple causes of this event. However, our results indicate that ISO trades had a profound impact on the market conditions that developed prior to the Flash Crash.

Our primary recommendation is for the SEC to implement an ISO halt during periods of high market wide volatility. This halt should have the following stabilizing affects on the market. First, without the ISO trade, traders will not be able to reach beyond the current best price of the market and execute a market depth sweep. This aspect of ISOs acts like a plunger, pressing down across all market centers at the same time, as a series of sweep orders consumes all posted liquidity at better prices. Second, if traders are limited to only NSO trades, these trades are subject to auto routing. For example, if a market has a posted depth of 1,500 shares and a trader sends a NSO order to that market for 5,000 shares, the first 1,500 will be filled, but the balance of the order will be subject to re-routing to another market center that now has the best price. This re-routing slows down the ability of liquidity demanders to obtain counter party depth and allows the book to replenish at the initial market center. In addition, exchange based routing is not free; currently the typical charge is 30 cents per 100 shares. This changes the cost structure of demanding liquidity and can induce some liquidity demanders to become liquidity suppliers. Finally, this halt would put all traders on the same level. Large institutional traders, with advanced trading programs, could not use ISOs to their advantage in capturing liquidity at current prices, predicting the prices will move substantially in the future, as smaller investors are locked into NSO trades or ISO trades that do not have the order size necessary to execute a market depth sweep.

5.0 Conclusion

The Flash Crash of 6 May 2010 raises serious questions about the structure and stability of US financial markets. We investigate one structural issue that may have contributed to the rapid drop and recovery of stock prices. This structural defect was introduced with Regulation NMS and is contained in the Order Protection Rule, Rule 611. Specifically, this rule creates an exemption to order protection that allows traders to trade through the best prices in the market, the Intermarket Sweep Order (ISO). An ISO is a limit order designated for quick and automatic execution in a specific market. It will be executed in the designated market center even if another market center is publishing a better quote. When submitting an ISO, the initiating trader also needs to fulfill Reg NMS order protection obligations by concurrently sending orders, also marked as ISO trades, to all other markets centers publishing better quotations. These orders must at least match, in total, the posted depth on each market center with better prices.

We find that ISO use increases significantly on the day of the Flash Crash. Our analysis indicates that ISO order flow was highly informed, relative to Non-Sweep Order (NSO) trades, based on the information share method of Hasbrouck (1995), beyond the volume share of ISO trades. We also show that the trade through capabilities of ISO trades is used more extensively on the day of the Flash Crash than during the reference period. Specifically, ISO trade throughs increased three fold in the thirty minutes prior to the Flash Crash, relative to the previous thirty minutes and represent a 5 fold increase over the same time frame within the reference period.

On the afternoon of the day of the crash, before the price drop, significant liquidity was withdrawn from the market. Our analysis indicates that, as markets become less liquid, the use of ISO trades increases. In addition, ISO use is positively serially correlated implying that increases of ISO use are followed by even larger increases. These two results indicate that market conditions conspired to increase trading aggressiveness just as the market was least positioned to accommodate this aggressive trading.

While there is no test to find the direct cause of the Flash Crash, our results indicate that the ISO exemption helped contribute to the destabilization of the market. Under normal market conditions, ISO trades are productive and a useful addition to the traditional trade types. However, from a policy perspective, we feel the SEC should consider instigating an ISO halt mechanism that will stop ISO trading when markets become volatile. This halt would naturally slow the markets and increase the costs of demanding liquidity. These two aspects of an ISO halt will help reduce the volatility that is experienced when markets become stressed.

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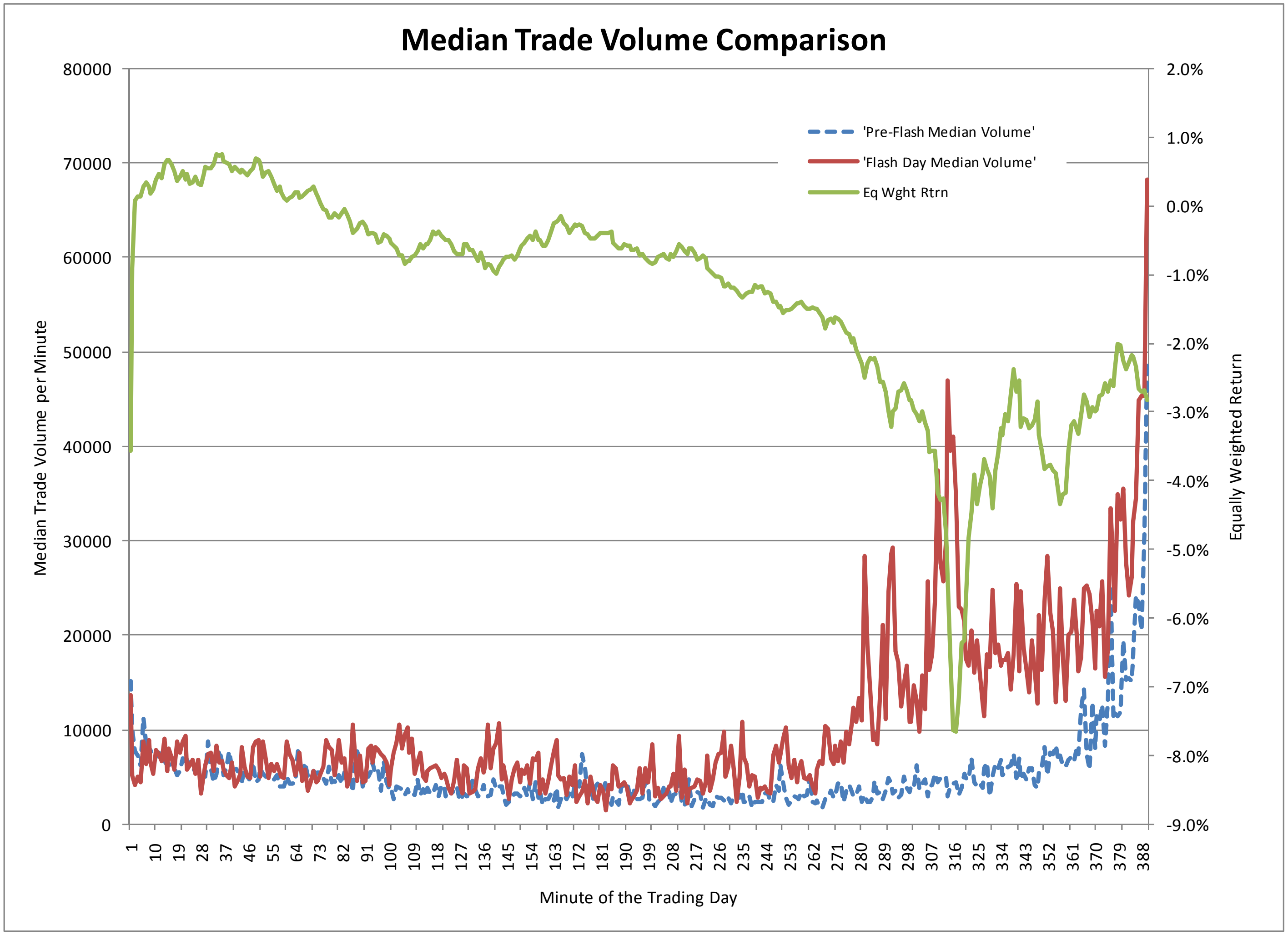

Fig 1. Median trade volume comparison for the day of the Flash Crash and the prior three day pre-flash period. Median trading volumes are plotted for the 500 stocks in the S&P500. The equally weighted return is plotted for the day of the Flash Crash for reference and is based on the opening price of each stock. Only exchange executed volumes are considered, trades only reported through an exchange are dropped.

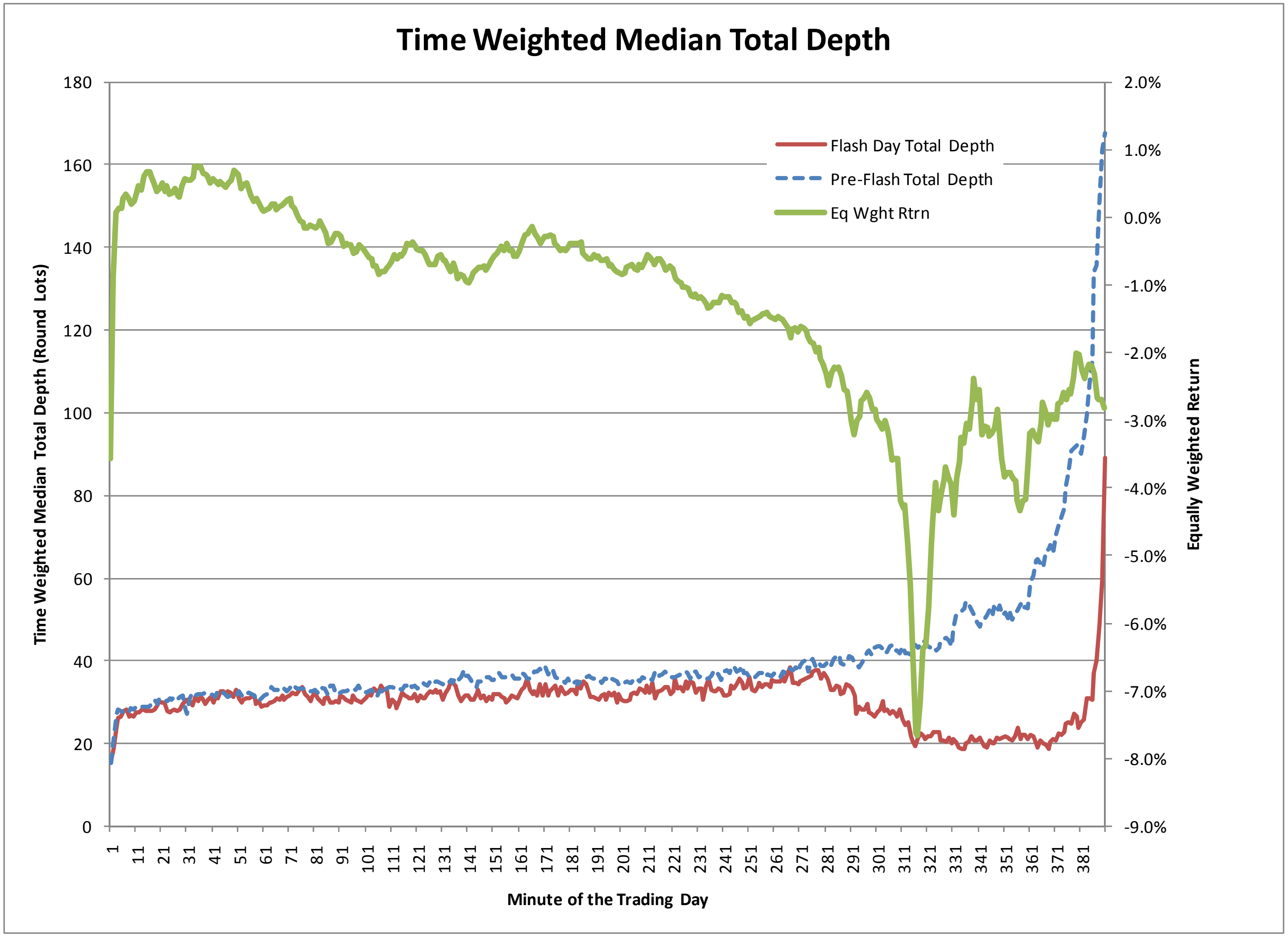

Fig 2. Time weighted median quoted depth comparison for the day of the Flash Crash and the prior three day pre-flash period. Median total quoted depths are plotted for the 500 stocks in the S&P500. The equally weighted return is plotted for the day of the Flash Crash for reference and is based on the opening price of each stock.

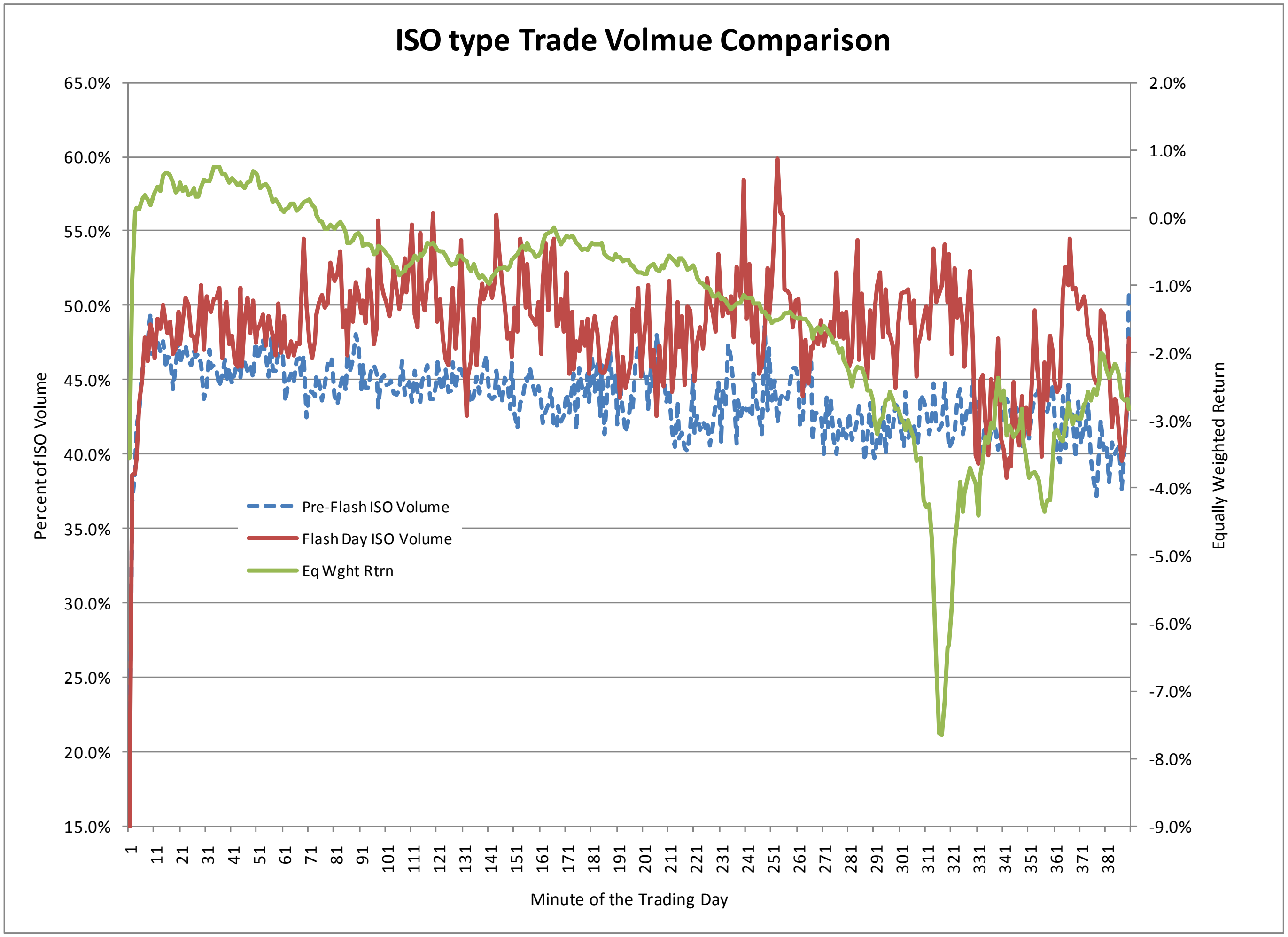

Fig 3. Comparison of the percentage of ISO trade volume for the day of the Flash Crash compared to the prior three day pre-flash period. Percentage of ISO volume is the equally weighted average for the 500 stocks in the S&P500. The equally weighted return is plotted for the day of the Flash Crash for reference and is based on the opening price of each stock. Only exchange executed volumes are considered, trades only reported through an exchange are dropped.

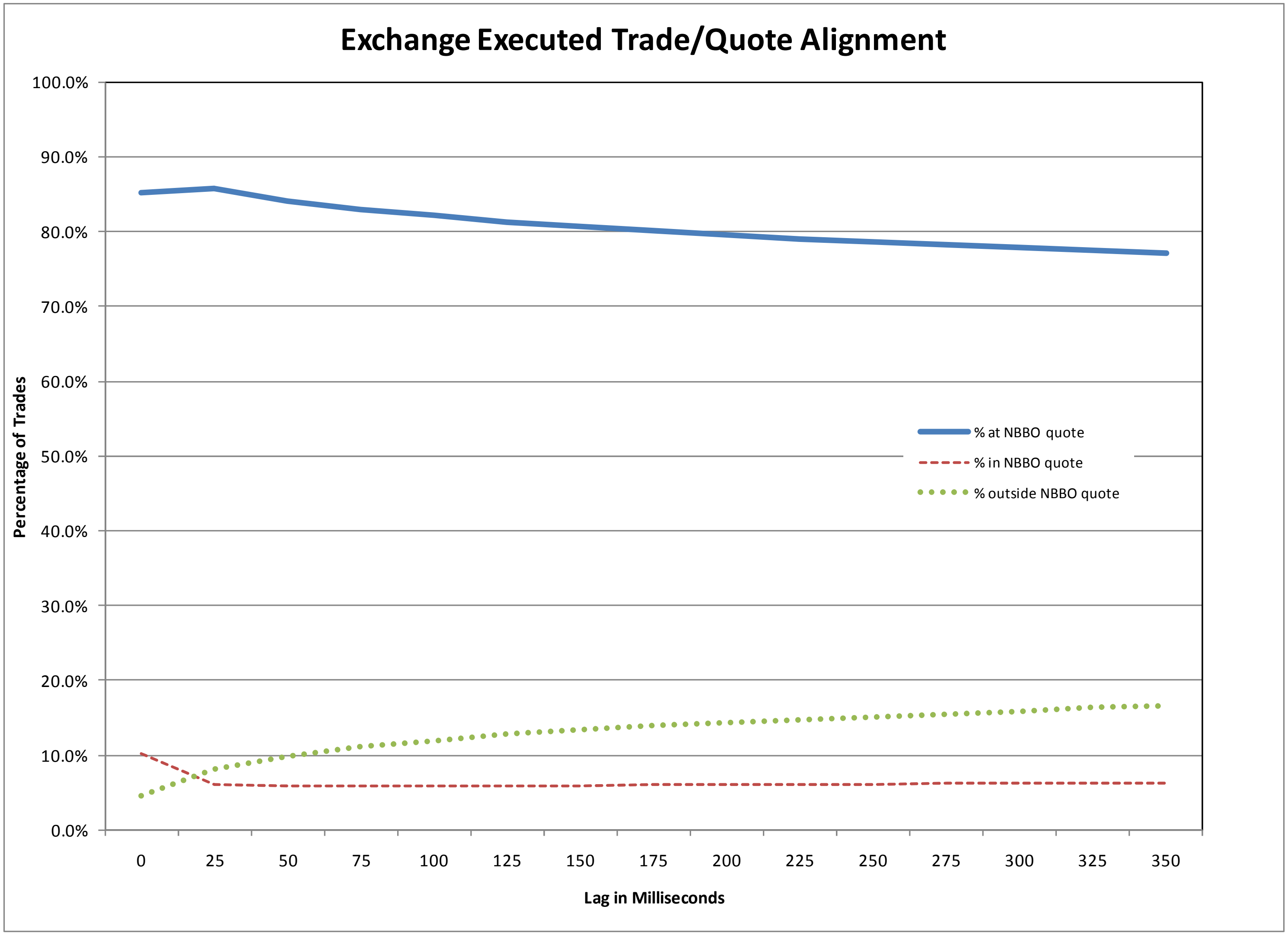

Figure 4: Exchange executed trade and NBBO quote alignment results. We plot the average percent of trades, ISO and NISO, which execute at the NBBO quote, inside the NBBO quote, and outside the NBBO quote, as a function of the lag time between the NBBO quote time stamp and the time stamp of the trade.

Table 1

Intermarket sweep order volume analysis

This table evaluates the observed increase in ISO trade volume on the day of the Flash Crash. The pre-flash period represents the three prior days of trading. Parametric tests are based on a paired t-test while non-parametric tests are based on the Wilcoxn Rank Sum test. The sample consists of the 500 stocks in the S&P 500. The trading day is divided into 13 thirty minute segments. Total trade volume is bifurcated as either ISO or NSO trades. Only exchange executed trade volume is considered, non-Trade Reporting Facility (TRF) trades. Results represent the average and median percent of ISO volume.

	Mean Percent Volume			Median Percent Volume		
Period	Flash	Base	Diff	Flash	Based	Diff
1	46.00	44.78	1.22**	45.87	44.93	0.93*
2	48.68	45.85	2.83**	48.92	46.39	2.53**
3	49.45	45.22	4.23**	49.58	45.69	3.89**
4	51.15	44.80	6.35**	51.59	45.21	6.39**
5	49.41	44.80	4.61**	48.96	45.64	3.32**
6	49.70	43.75	5.96**	49.65	43.58	6.07**
7	46.91	44.62	2.28**	47.19	45.02	2.17**
8	49.06	42.63	6.43**	49.11	42.31	6.80**
9	50.12	43.98	6.13**	50.70	44.08	6.61**
10	48.67	41.66	7.01**	48.32	41.83	6.49**
11	49.91	42.39	7.52**	50.19	42.26	7.93**
12	42.99	42.41	0.58	43.13	41.47	1.66
13	47.04	41.40	5.64**	47.08	41.07	6.01**

Table 2

Information share of ISO order flow

These results are based on the information shares method of Hasbrouck (1995). The information share of ISO and NSO trades are estimated for each stock day period of the sample. The base results are the average information share for ISO trades for the three days prior to the Flash Crash. Information shares are also estimated on the day of the Flash Crash. Diff represents the paired difference for the measure between the day of the Flash Crash and the base period. InfoRatio (the information ratio) is the defined as the ratio of the information share of ISO trades for stock *i* divided by the percentage of ISO volume for stock *i*, on day *t* and period *k*. Specifically the information gap is defined as:

$$InfoRatio_{i,t,k} = InfoShr_{i,t,k} \,/\, \%ISOvol_{i,t,k}$$

An information ratio over 1 means that the trade type carries information beyond the volume contribution. An information ratio under 1 means that the trade type carries information below the volume contribution. To estimate the information share we create two price channels, one for ISO trade prices and one for NSO trade prices. Only exchange executed trades are considered in the analysis. We use the last trade in each second of the trading day for each price channel. The sample consists of the stocks in the S&P500. Each period represents 30 minutes of trading. For each period we test if the information ration if ISO trades on the day of the Flash Crash are significantly different from a value of 1.0.

	Information Share			Information Ratio		
Period	Flash	Base	Diff	Flash	Base	Diff
1	0.462	0.470	-0.008	1.063[aa]	1.145	-0.082**
2	0.534	0.488	0.046**	1.095[aa]	1.066	0.028
3	0.541	0.511	0.030**	1.107[aa]	1.129	-0.022
4	0.539	0.512	0.027**	1.068[aa]	1.158	-0.090**
5	0.548	0.509	0.039**	1.122[aa]	1.147	-0.025
6	0.560	0.495	0.065**	1.138[aa]	1.151	-0.013
7	0.522	0.518	0.004	1.146[aa]	1.188	-0.042
8	0.529	0.502	0.027**	1.090[aa]	1.206	-0.116**
9	0.552	0.519	0.033**	1.115[aa]	1.188	-0.074**
10	0.514	0.497	0.017*	1.045[aa]	1.220	-0.176**
11	0.525	0.497	0.028**	1.049[aa]	1.181	-0.132**
12	0.440	0.507	-0.067**	1.006	1.223	-0.217**
13	0.504	0.493	0.011	1.068[aa]	1.175	-0.107**

* significant at the 5% level

** significant at the 1% level

[a] significantly different from 1.0 at a 5% level

[aa] significantly different from 1.0 at a 1% level

Table 3

Trade quote alignment

Although the DTAQ database contains time stamps to the millisecond, this does not guarantee that the current NBBO quote is the in force quote at the time of the trade. To align trades and NBBO quotes we use the following process. We recognize that the vast majority of trade executions occur in the matching engines of the different market centers, without human interaction. We therefore believe that the most appropriate lag time adjustment between the NBBO quote and the trade will be the time that maximizes the number of trades executing at NBBO prices. For each stock day period we evaluate the percentage of trades that execute at NBBO prices for lags times between 0 and 250 milliseconds in 25 millisecond increments. We then apply the optimum lag to each stock day period when the trade price is to be referenced to the in force NBBO price. We report the average lag time, in milliseconds,

	Lag		In Quote		ISO in Quote		NISO in Quote	
Period	Flash	Base	Flash	Base	Flash	Base	Flash	Base
1	12.3	7.6	94.1	94.3	91.1	91.0	95.7	95.9
2	13.3	9.5	94.7	95.6	92.6	93.2	96.1	96.9
3	13.9	9.7	94.7	95.5	92.9	93.4	96.0	96.7
4	9.9	11.7	94.7	95.9	92.6	93.9	96.1	97.1
5	11.7	11.9	94.7	96.1	92.6	94.1	96.0	97.2
6	13.5	11.7	95.1	96.1	93.2	94.0	96.4	97.2
7	14.5	12.5	95.4	95.8	93.5	93.7	96.7	97.0
8	14.4	13.2	94.4	96.3	92.3	94.4	95.8	97.4
9	13.3	13.2	94.8	95.8	92.6	93.8	96.2	96.9
10	11.1	12.5	93.3	96.4	90.9	94.3	94.8	97.4
11	12.0	9.3	86.3	96.2	82.8	94.3	88.7	97.2
12	12.7	9.1	91.6	96.3	87.2	94.4	93.8	97.3
13	13.0	6.2	92.0	96.6	88.4	95.1	94.1	97.5

Table 4

ISO and NSO trade through analysis

Perhaps one of the most important aspects of ISO orders is their regulatory ability to trade through best prices in the market. Specifically, if the ISO initiator wishes to access liquidity outside of best prices, she must simultaneously submit ISO orders to all market centers posting better prices with sufficient volume to take out the posted depth at the top of the book for each market center. However, an ISO will trade through best prices only when the target execution price is outside of the flicker quote, defined as the least aggressive NBBO ask and bid prices over the previous second. This table analyzes the median number of ISO and NSO trades that occur outside of flicker prices for the based period and the day of the Flash Crash. The analysis is conducted for each 30 minute period of the trading day. We report the median number of trade throughs for each order for the Based and Flash days. We also report the difference of the medians. We conduct a Wilcoxn Rank Sum test to see if the sample of trade throughs differs between the base and Flash days.

	ISO						NSO					
	Over Ask			Under Bid			Over Ask			Under Bid		
Period	Flash	Base	Dif	Flash	Base	Dif	Flash	Base	Dif	Flash	Base	Dif
Panel A: Mean evaluation of trade throughs												
1	35.9	39.4	-3.5	26.2	29.7	-3.5*	11.0	12.4	-1.5	7.9	8.3	-0.4
2	28.7	26.2	2.5	19.2	21.0	-1.7	7.7	8.4	-0.7	5.8	6.0	-0.2
3	27.2	21.0	6.1**	23.0	22.6	0.4	7.5	6.3	1.3	6.3	6.8	-0.5
4	31.5	15.1	16.4**	24.1	13.0	11.1**	7.6	4.7	2.9**	5.9	4.2	1.7**
5	25.1	11.3	13.8**	25.7	10.1	15.7**	4.7	4.1	0.6	13.5	3.0	10.5*
6	25.0	9.4	15.6**	13.4	12.1	1.3	5.7	3.6	2.1**	3.4	3.7	-0.4
7	12.6	12.3	0.2	11.1	8.1	3.0**	3.2	3.6	-0.4	2.3	3.4	-1.1**
8	21.0	8.3	12.7**	17.1	7.6	9.5**	4.6	2.6	2.0**	2.9	2.4	0.5
9	23.8	11.6	12.2**	15.1	9.5	5.6**	5.7	3.5	2.2**	4.1	2.6	1.5**
10	60.2	9.9	50.3**	55.3	10.2	45.1**	19.3	3.0	16.3**	19.0	2.8	16.1**
11	206.0	16.8	189.3**	232.5	15.5	217.0**	102.2	5.4	96.8**	122.3	4.1	118.2**
12	109.4	19.6	89.8**	82.1	13.9	68.1**	37.4	5.4	32.0**	26.2	4.7	21.5**
13	119.8	29.6	90.2**	92.4	23.6	68.8**	30.8	10.5	20.2**	20.3	8.6	11.7**

Table 4 continued

Panel B: Median evaluation of trade throughs

1	12.0	14.0	-2.0	9.0	11.0	-2.0	4.0	4.0	0.0	2.0	2.0	0.0
2	10.0	8.0	2.0*	6.0	6.0	0.0	2.0	2.0	0.0	1.0	1.0	0.0
3	8.0	6.0	2.0**	7.0	7.0	0.0*	2.0	1.0	1.0*	1.0	1.0	0.0
4	10.0	4.0	6.0**	7.0	3.0	4.0**	3.0	1.0	2.0**	1.0	1.0	0.0**
5	8.0	3.0	5.0**	5.0	3.0	2.0**	1.0	1.0	0.0*	1.0	0.0	1.0**
6	7.0	3.0	4.0**	3.0	3.0	0.0*	1.0	1.0	0.0**	1.0	0.0	1.0
7	4.0	4.0	0.0*	3.0	3.0	0.0**	1.0	0.0	1.0	0.0	0.0	0.0
8	6.0	2.0	4.0**	5.0	2.0	3.0**	1.0	0.0	1.0**	1.0	0.0	1.0**
9	8.0	3.5	4.5**	5.0	2.0	3.0**	2.0	0.0	2.0**	1.0	0.0	1.0**
10	24.5	2.0	22.5**	21.0	2.0	19.0**	7.5	0.0	7.5**	6.0	0.0	6.0**
11	94.5	5.0	89.5**	87.0	4.0	83.0**	43.5	1.0	42.5**	34.0	1.0	33.0**
12	53.5	7.0	46.5**	35.5	4.0	31.5**	18.0	1.0	17.0**	9.0	1.0	8.0**
13	63.0	12.0	51.0**	51.0	10.0	41.0**	17.0	4.0	13.0**	10.0	3.0	7.0**

* significant at the 5% level

** significant at the 1% level

Table 5

Liquidity comparison

We examine changes in quote based liquidity on the day of the Flash Crash. Depths are based on the total posted liquidity that is available for immediate execution, ie all depth at or inside the flicker price. Ask results are shown in Panel A and Bid results are shown in Panel B. Breadth represents the time weighted number of market centers offering depth for immediate execution. Each period represents 30 minutes. To control for outliers, quoted depths greater than 5,000 round lots are dropped from the analysis. This constraint removes Citigroup (C) from the analysis. Results are shown in round lots.

	Depth		Depth STD		Breadth		Breadth STD	
Period	Flash	Base	Flash	Base	Flash	Base	Flash	Base
Panel A: Ask Quote								
1	37.7	36.7	6.58	6.78	4.66	4.69	0.48	0.47
2	55.0**	50.9	5.35	5.33	5.07	5.04	0.11**	0.06
3	60.1**	63.7	6.38**	2.88	5.13	5.13	0.10**	0.06
4	60.3**	66.1	4.63	3.85	5.26**	5.17	0.11*	0.07
5	62.8**	69.6	3.86**	2.03	5.16*	5.21	0.12**	0.05
6	63.8**	76.5	4.09	3.56	5.28	5.32	0.09	0.07
7	68.2**	72.6	5.95*	3.68	5.40*	5.31	0.20**	0.07
8	69.3**	76.9	5.56**	2.79	5.21**	5.35	0.09	0.08
9	71.1**	76.4	6.85**	3.44	5.27	5.30	0.11	0.08
10	66.9**	83.4	7.98**	4.03	5.26**	5.35	0.11*	0.07
11	40.0**	92.7	17.11**	4.07	5.18**	5.47	0.18**	0.08
12	27.3**	101.7	2.74**	6.29	5.08**	5.55	0.36**	0.10
13	48.9**	150.1	23.62**	40.99	5.24**	5.78	0.35**	0.10
Panel B: Bid Quote								
1	36.4	39.1	7.20	7.50	4.60	4.64	0.52	0.55
2	51.7	53.7	3.56**	6.14	5.02	5.02	0.09	0.10
3	57.3**	64.1	5.01	3.55	5.02**	5.09	0.09	0.08
4	60.2**	69.0	4.95	4.60	5.01**	5.14	0.11	0.09
5	61.1**	75.2	4.16	3.53	4.95**	5.29	0.09	0.07
6	61.5**	73.9	5.04*	3.46	5.04**	5.24	0.09	0.07
7	65.6**	75.1	5.27*	3.46	4.99**	5.26	0.12**	0.05
8	61.0**	77.4	4.31	3.75	5.05**	5.24	0.09*	0.06
9	65.5**	77.4	5.17	4.96	5.07**	5.26	0.10	0.08
10	65.1**	82.2	5.24	5.11	4.98**	5.26	0.16**	0.07
11	41.1**	90.6	14.87**	6.08	4.30**	5.36	0.37**	0.08
12	29.3**	101.9	4.16**	7.21	4.26**	5.42	0.13	0.10
13	50.8**	152.8	27.31	39.16	4.44**	5.57	0.15	0.15

* significantly different from the base period at the 5% level

** significantly different from the base period at the 1% level

Table 6

Fixed effects regression

This table examines the relationship between changes in market depth and changes in the percentage of volume traded with Intermarket Sweep Orders. We estimate the following regression:

$$\Delta\%ISO_{i,t} = \alpha + \sum_{k=1}^{2} \beta_k \Delta\%ISO_{i,t-k} + \beta_3 \Delta\%Dpth_{i,t} + \beta_4 Dx + \beta_5 LnMcap_i + \varepsilon_{i,t}$$

We first calculate the average percent of ISO volume and Depth for each minute of the trading day in the based period and on the day of the Flash Crash, 390 minutes per period. We next take the difference ISO volume and Depth. Δ%ISO represents the difference in the percentage of ISO volume, $\%ISO_{Flsh}$-$\%ISO_{Base}$. Δ%Dpth represents the percentage change in total depth, $(Dpth_{Flsh}-Dpth_{Base})/Dpth_{Base}$. Dx is a dummy variable that is 1 on and after minute 302 (2:32 pm EST) which is the time that a75,000 mini-E contract sale order was initiated. In the cross sectional analysis we include the natural log of market capitalization as a cross sectional control. For the stock level regression we estimate the regression for each stock and then average the coefficients and test if they are significantly different from zero. Standard errors are adjusted for heteroscedasticity.

Variable	Market Level	Cross Sectional	Stock Level
Intercept	0.010**	-0.026**	0.033**
Δ%ISO$_{t-1}$	0.368**	0.174**	0.137**
Δ%ISO$_{t-2}$	0.287**	0.135**	0.089**
Δ%Dpth	-0.027*	-0.022**	-0.027**
Dx	-0.010*	-0.012**	-0.017**
LnMcap		0.004**	
Adj R-Sq	0.353	0.062	0.068

* significant at the 5% level

** significant at the 1% level

Table 7

Volume imbalance for ISO and NSO order flow

Volume imbalance is defined as (Buy Volume-Sell Volume)/(Buy Volume-Sell Volume). For each stock day 30 minute period of the trading day we sum buy and sell volume and then calculate the volume order imbalance. Trade inference is based on the method of Lee and Ready (1991) and the reference quote for in each period is based on the optimal lag time. ISO and NSO volume are evaluated separately. Only exchange executed volume are considered in the analysis.

	ISO order flow		NSO order flow	
Period	Flash	Base	Flash	Base
1	-2.09	-2.02	0.06	-0.41
2	0.73	1.18	-1.15	-0.86
3	-1.54	-4.40	-3.12	-3.78
4	3.43	0.02	-3.72	-2.06
5	1.03	3.38	-3.52	2.77
6	6.23	-1.02	-0.36	-2.96
7	-4.20	6.22	-4.05	0.40
8	-4.14	-1.77	-5.46	-3.14
9	-0.24	1.44	-4.35	0.11
10	-2.82	-2.75	-6.78	-2.95
11	-7.30	-0.80	-9.36	-3.16
12	-0.37	0.95	-12.94	-2.50
13	-2.20	0.10	-2.17	-0.68

Table 8

Volume Imbalance and Returns

The impact of trade volume imbalance on NBBO quote midpoint returns is evaluated. Group represents the number of minutes in a trading day that returns and volume imbalances are based on. If Group is 5 then there are 78 five minute segments each day. N represents the total number of segments contained in the regression. We estimate the following two regressions to evaluate the impact of ISO volume imbalance, NSO volume imbalance and Total volume imbalance:

$$Rtrn_{i,t} = \alpha + \sum_{k=1}^{n} Rtrn_{i,t-k} + \sum_{k=0}^{j} Ibal_{i,t-k} + \sum_{k=0}^{m} Nbal_{i,t-k} + Flsh_t + \varepsilon_{i,t}$$

And

$$Rtrn_{i,t} = \alpha + \sum_{k=1}^{n} Rtrn_{i,t-k} + \sum_{k=0}^{h} Tbal_{i,t-k} + Flsh_t + \varepsilon_{i,t}\,.$$

Where *Rtrn* is the return of the NBBO quote midpoint for each segment, *Ibal* volume imbalance of ISO trades, *Nbal* is the volume imbalance of NSO trades, *Tbal* is the total volume imbalance, and *Flsh* is a dummy variable that is 1 if the segment is after the 300 minute mark on 6 May 2010, the day of the Flash Crash. Volume imbalance is based on (BuyVol-SellVol)/(BuyVol+SellVol). Trade inference is based on Lee and Ready (1991). The in force NBBO quote is used for trade direction inference based on the optimal quote lag condition. Panel A shows the results for the market, where the quote midpoint return is evaluated for each individual stock in the sample and then equally weighted and volume imbalances are for the full market. Panel B is shows the results based on a cross sectional fixed effects regression at the stock level. Stock returns for this regression are adjusted by subtracting the equally weighted return of all sample stocks. Only exchange executed trades are included in the analysis. Lagged values of *Rtrn*, *Ibal*, *Nbal*, and *Tbal* are included in each regression until they are no longer significant and the number of included lags can vary by regression. Standard errors are adjusted for heteroscedasticity. We report only the coefficients from the first lag of *Rtrn* and the contemporaneous volume imbalance variables.

Group	N	Intercept	Rtrn	Ibal	Nbal	Tbal	Flsh	R^2
Panel A: Market Return Regression								
5	308	0.0000	0.1735	0.0055***	-0.0013		0.0003	0.063
5	308	0.0000	0.1819			0.0043***	0.0004	0.057
10	152	-0.0002	0.0474	0.0144*	-0.0115		0.0004	0.019
10	152	-0.0001	0.0417			0.0045	0.0011	-0.007
Panel B: Cross Sectional Fixed Effects Regression								
5	139307	0.0000	-0.7158***	0.0002***	0.0000		0.0001	0.340
5	135795	0.0000	-0.8273***			-0.0071*	-0.0004	0.405
10	61927	-0.0002	-0.8526***	-0.0005	-0.0001		0.0003	0.331
10	57931	-0.0003	-0.7445***			-0.0009	0.0003	0.227

* significant at the 10% level
** significant at the 5% level
*** significant at the 1% level

Table 9

Information share of ISO orderflow, All trades included

These results are based on the information shares method of Hasbrouck (1995). The information share of ISO and NSO trades are estimated for each stock day period of the sample. The base results are the average information share for ISO trades for the three days prior to the Flash Crash. Information shares are also estimated on the day of the Flash Crash. Diff represents the paired difference for the measure between the day of the Flash Crash and the base period. InfoRatio (the information ratio) is the defined as the ratio of the information share of ISO trades for stock *i* divided by the percentage of ISO volume for stock *i*, on day *t* and period *k*. Specifically the information gap is defined as:

$$InfoRatio_{i,t,k} = InfoShr_{i,t,k} / \%ISOvol_{i,t,k}$$

An information ratio over 1 means that the trade type carries information beyond the volume contribution. An information ratio under 1 means that the trade type carries information below the volume contribution. To estimate the information share we create two price channels, one for ISO trade prices and one for NSO trade prices. As a robustness check, all trades, TRF and exchange executed, are included. We use the last trade in each second of the trading day for each price channel. The sample consists of the stocks in the S&P500. Each period represents 30 minutes of trading. For each period we test if the information ration if ISO trades on the day of the Flash Crash are significantly different from a value of 1.0.

	Information Share			Information Ratio		
Period	Flash	Base	Diff	Flash	Base	Diff
1	0.462	0.470	-0.008	1.362[aa]	1.450	-0.088*
2	0.534	0.488	0.046**	1.429[aa]	1.399	0.031
3	0.541	0.511	0.030**	1.406[aa]	1.472	-0.065*
4	0.539	0.512	0.027**	1.373[aa]	1.546	-0.173**
5	0.548	0.509	0.039**	1.457[aa]	1.531	-0.074*
6	0.560	0.495	0.065**	1.472[aa]	1.525	-0.053
7	0.522	0.518	0.004	1.457[aa]	1.540	-0.083**
8	0.529	0.502	0.027**	1.397[aa]	1.579	-0.182**
9	0.552	0.519	0.033**	1.432[aa]	1.549	-0.117**
10	0.514	0.497	0.017*	1.293[aa]	1.592	-0.299**
11	0.525	0.497	0.028**	1.208[aa]	1.547	-0.339**
12	0.440	0.507	-0.067**	1.137[aa]	1.551	-0.414**
13	0.504	0.493	0.011	1.203[aa]	1.411	-0.207**

* significant at the 5% level

** significant at the 1% level

[a] significantly different from 1.0 at a 5% level

[aa] significantly different from 1.0 at a 1% level

Table 10

Volume Imbalance and Returns, All Trades

The impact of trade volume imbalance on NBBO quote midpoint returns is evaluated. Group represents the number of minutes in a trading day that returns and volume imbalances are based on. If Group is 5 then there are 78 five minute segments each day. N represents the total number of segments contained in the regression. We estimate the following two regressions to evaluate the impact of ISO volume imbalance, NSO volume imbalance and Total volume imbalance:

$$Rtrn_{i,t} = \alpha + \sum_{k=1}^{n} Rtrn_{i,t-k} + \sum_{k=0}^{j} Ibal_{i,t-k} + \sum_{k=0}^{m} Nbal_{i,t-k} + Flsh_t + \varepsilon_{i,t}$$

And

$$Rtrn_{i,t} = \alpha + \sum_{k=1}^{n} Rtrn_{i,t-k} + \sum_{k=0}^{h} Tbal_{i,t-k} + Flsh_t + \varepsilon_{i,t}.$$

Where *Rtrn* is the return of the NBBO quote midpoint for each segment, *Ibal* volume imbalance of ISO trades, *Nbal* is the volume imbalance of NSO trades, *Tbal* is the total volume imbalance, and *Flsh* is a dummy variable that is 1 if the segment is after the 300 minute mark on 6 May 2010, the day of the Flash Crash. Volume imbalance is based on (BuyVol-SellVol)/(BuyVol+SellVol). Trade inference is based on Lee and Ready (1991). The in force NBBO quote is used for trade direction inference based on the optimal quote lag condition. Panel A shows the results for the market, where the quote midpoint return is evaluated for each individual stock in the sample and then equally weighted and volume imbalances are for the full market. Panel B is shows the results based on a cross sectional fixed effects regression at the stock level. Stock returns for this regression are adjusted by subtracting the equally weighted return of all sample stocks. All trades, TRF and exchange executed trades are included in the analysis. Lagged values of *Rtrn*, *Ibal*, *Nbal*, and *Tbal* are included in each regression until they are no longer significant and the number of included lags can vary by regression. Standard errors are adjusted for heteroscedasticity. We report only the coefficients from the first lag of *Rtrn* and the contemporaneous volume imbalance variables.

Group	N	Intercept	Rtrn	Ibal	Nbal	Tbal	Flsh	R^2
Panel A: Market Return Regression								
5	308	0.0000	0.1872	0.0030**	0.0030		0.0004	0.071
5	308	0.0000	0.1861			0.0061***	0.0005	0.073
10	152	-0.0001	0.0528	0.0053	0.0029		0.0011	0.004
10	152	0.0000	0.0512			0.0086*	0.0012	0.010
Panel B: Cross Sectional Fixed Effects Regression								
5	147626	0.0000	-0.5489**	0.0001***	0.0000		-0.0001	0.257
5	135823	0.0000	-0.8349***			-0.0051	-0.0003*	0.408
10	69932	0.0000	-0.6229**	-0.0006	0.0001		0.0000	0.188
10	57973	-0.0002	-0.8613***			-0.0011	0.0003	0.421

* significant at the 10% level

** significant at the 5% level

*** significant at the 1% level