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Impact of Stock Market Structure on Intertrade Time and Price Dynamics

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Abstract
We analyse times between consecutive transactions for a diverse group of stocks registered on the NYSE and NASDAQ markets, and we relate the dynamical properties of the intertrade times with those of the corresponding price fluctuations. We report that market structure strongly impacts the scale-invariant temporal organisation in the transaction timing of stocks, which we have observed to have long-range power-law correlations. Specifically, we find that, compared to NYSE stocks, stocks registered on the NASDAQ exhibit significantly stronger correlations in their transaction timing on scales within a trading day. Further, we find that companies that transfer from the NASDAQ to the NYSE show a reduction in the correlation strength of transaction timing on scales within a trading day, indicating influences of market structure. We also report a persistent decrease in correlation strength of intertrade times with increasing average intertrade time and with corresponding decrease in companies’ market capitalization—a trend which is less pronounced for NASDAQ stocks. Surprisingly, we observe that stronger power-law correlations in intertrade times are coupled with stronger power-law correlations in absolute price returns and higher price volatility, suggesting a strong link between the dynamical properties of intertrade times and the corresponding price fluctuations over a broad range of time scales. Comparing the NYSE and NASDAQ markets, we demonstrate that the stronger correlations we find in intertrade times for NASDAQ stocks are associated with stronger correlations in absolute price returns and with higher volatility, suggesting that market structure may affect price behavior through information contained in transaction timing. These findings do not support the hypothesis of universal scaling behavior in stock dynamics that is independent of company characteristics and stock market structure. Further, our results have implications for utilising transaction timing patterns in price prediction and risk management optimization on different stock markets.


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Introduction

The impact of market structure and associated rules of operation on market efficiency and stock price formation have attracted considerable public attention [1]. Developments on the New York Stock Exchange (NYSE) [1,2], have raised the profile of the market operating mechanism, the “market structure”, employed by a stock market. This has also been of concern to those involved in stock market regulation, on behalf of investors [1,3], since optimizing market structure results in more effectively functioning markets [4] and increases competitiveness for market share in listed stocks [5]. The two major stock markets in the U.S., the NYSE and the National Association of Securities Dealers Automated Quotation System (NASDAQ) National Market have very different structures [6,7], and there is continuing controversy over whether reported differences in stock price behavior are due to differences in market structure or company characteristics [8]. Comparative studies of the NYSE and NASDAQ have primarily focused on stock prices to provide evidence that market organizational structure affects the price formation process [4,9,10]. It has been shown that stocks registered on the NASDAQ may be characterized by a larger bid-ask spread [11] and higher price volatility [4,9,10]. However, this is often attributed to the market capitalization, growth rate or the nature of the companies listed on the NASDAQ [9]. Empirical studies have also emphasized the dominant role and impact of trading volume on prices [12,13]; since traded volume is determined by investors it is difficult to isolate the effects of market structure on price formation. As the influence of market structure on stock prices may be obscured by exogenous factors such as demand and supply [12,13], we hypothesize that modulation of the flow of transactions due to market operations may carry a stronger imprint of the internal market mechanism.

Here we analyse times between consecutive transactions for a diverse group of stocks registered on the NYSE and NASDAQ markets, and we relate the dynamical properties of the intertrade times with those of the corresponding price fluctuations. To understand how market structure may affect stock prices, we study...
the information contained in the times between consecutive stock transactions. As market-specific operations may modulate the flow of transactions, we hypothesize that dynamical features of transaction timing reflect the underlying market mechanism. Specifically, we ask if stocks of companies with diverse characteristics registered on a given market exhibit common features in their transaction timing, which may be associated with the particular market structure. Further, we investigate how the dynamical properties of transaction timing over a range of time scales relate to stock price dynamics and whether market structure affects the temporal organisation of price fluctuations.

To probe how market structure influences the trading of stocks, we consider the two major U.S. stock markets, the NYSE and the NASDAQ. All transactions on the NYSE of a given stock are centralised and are controlled by a single human operator called a "specialist", whose primary role is to match together public buy and sell orders on the basis of price, in an auction-like setting [6]. The NYSE specialist is under obligation to maintain both price continuity and a "fair and orderly market" [6], as well as to intervene, using his own firm's inventory of available stock, to provide liquidity in the event of an order imbalance, thus preventing sharp changes in the stock price [6]. The NYSE regulations allow for considerable flexibility within the specialist's operations [2].

In contrast, trading on the NASDAQ is decentralised, with trading in a given stock managed by a number of dealers called "market makers". These market makers maintain a stock inventory, posting their best prices at which they are prepared to immediately buy and sell stock [7]. Market makers compete with each other for orders, so in theory competition ensures that investors get the best prices. Alternatively, an order can be placed into an Alternative Trading System (ATS), operated by NASD members or NASD-member affiliates and designed to allow two subscribers to meet directly on the system under the regulation of a third party. The most commonly used form of ATS is the Electronic Communication Network (ECN), a facility that matches customer buy and sell orders directly through a computer network.

A third alternative, in case the order placed is very small, is to enter the order into the Small Order Execution System (SOES), which is an electronic network designed to allow fast automatic routing, execution and reporting of orders of 500 shares or less. Orders are automatically routed to market makers whose quotes are currently identical to the highest bid (buy) and the lowest offer (sell) prices. Participation in the SOES system was made mandatory [7] after the market crash of October 1987, as one of the reported problems on the NASDAQ during the crash was the inability to reach market makers by the phone during periods of rapid price movement.

To summarize the differences between the two market structures, each market maker on the NASDAQ maintains his own inventory of stock in order to buy and sell [7]. In comparison, the NYSE specialist rarely uses his own firm's inventory: such transactions involve less than 15% of trading volume [14]. Although several regional exchanges may trade NYSE listed stocks, price formation has primarily been attributed to NYSE trading [15]. In contrast, the NASDAQ market relies on competition between multiple dealers for public orders to facilitate the price formation process [11]. Moreover, a substantial fraction of share volume on the NASDAQ is not handled by dealers, but is traded electronically via networks for small public orders and for institutional investors [7]. Such fragmentation of the NASDAQ stock market has been associated with higher price volatility [4].

Here we ask to what extent such structural and operational differences between the NYSE and NASDAQ markets affect the flow of transactions. It is difficult to answer whether differences in intertrade times are due to individual company characteristics or external market influences (Fig. 1). Two empirical studies have considered only a single company stock over a short period of a few months [16,17]. Studies which considered a larger group of stocks either did not find common features in the intertrade times [18,19] or did not compare between markets [20–22]. The only comparative study considered a single NYSE and a single Paris stock, finding some differences in their intertrade times, but those may well be due to a different culture of trading [23]. To probe for evidence of the impact of market structure on the trading of stocks, we employ concepts and methods from statistical physics to investigate the correlation properties of transaction timing for

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<th>Company Name</th>
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<th>$T_{1}$ (sec)</th>
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<th>Ticker Symbol</th>
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Companies range in average market capitalisation from $30.8 \times 10^9$ to $1102 \times 10^9$ over the period, and are ranked in order of decreasing average value of ITT (777). We include all trades occurring during NYSE trading hours (9.30am–4pm EST), excluding public holidays and weekends.

doi:10.1371/journal.pone.0092885.t001
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Companies range in average market capitalisation from $0.2 \times 10^9$ to $5.4 \times 10^9$, and are ranked in order of decreasing average value of ITT ($\tau TT$). We include all trades occurring during regular NASDAQ trading hours (9.30am–4pm EST), excluding public holidays and weekends.

doi:10.1371/journal.pone.0092885.t002
Figure 2. Root-mean-square fluctuation function $F(n)$ obtained using DFA-2 analysis, for the intertrade times (ITT) of stock in NASDAQ company Sun Microsystems (SUNW) and NYSE company Compaq Computer Corp. (CPQ). Here $n$ indicates the time scale in number of trades. We normalize the time scale $n$ by the daily average number of trades for each stock, so that a unit normalized scale indicates one trading day (marked by a dashed line). The scaling curves are vertically offset for clarity. While both companies have similar market capitalisations, industry sectors and average levels of trading activity (average ITT) and exhibit long-range power-law correlations over a broad range of scales, the scaling behaviour of the intertrade times for the two stocks is quite different. For CPQ we find a pronounced crossover from weaker correlations over time scales smaller than a trading day, to stronger correlations over time scales larger than a trading day ($x_2^{ITT,CPQ} > x_1^{ITT,CPQ}$). In contrast, the scaling function $F(n)$ for SUNW does not exhibit such a crossover, and we find much stronger correlations over time scales smaller than a trading day compared with CPQ ($x_1^{ITT,CPQ} > x_2^{ITT,CPQ}$).

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diverse companies, over time scales ranging from seconds up to a year.

Data

We examine one hundred stocks listed on the NYSE, from eleven industry sectors: Technology-Hardware(5), Semiconductors(2), Pharmaceutical & Medical Equipment(10), Financial(3), Automotive(9), Defense/Aerospace(9), Mining, Metals & Steel Works(8), Chemicals & Plastics(7), Retail & Food(17), Petroleum, Gas & Heavy Machinery(10), Telephone Service Providers(7), Electric & Power Services(8). We study the time intervals between successive stock trades, over a period of four years–4 Jan. 1993 to 31 Dec. 1996 as recorded in the Trades and Quotes (TAQ) database from the NYSE (Table 1).

We also analyse one hundred NASDAQ stocks from fourteen industry sectors: Technology-Hardware(28), Technology-Software(16), Semiconductors(7), Pharmaceutical, Biotechnology & Medical Equipment(12), Financial(5), Automotive(1), Steel Works(1), Chemicals(1), Retail & Food(16), Petroleum, Gas & Heavy Machinery (2), Telephone & Cable Television Service Providers(5), Services(2), Transportation(3), Electrical Apparatus(1). We study the time intervals between successive stock trades as recorded in the TAQ database, for twenty-nine companies over the period 4 Jan. 1993–31 Dec. 1996, and seventy one companies over the period 3 Jan. 1994–30 Nov. 1995 (marked with (*) in Table 2). For both markets, we select companies with average market capitalisations ranging over three decades, and varying levels of trading activity with average values of intertrade time between 11 and 640 seconds for NYSE stocks, and between 5 and 680 seconds for NASDAQ stocks. In parallel with the intertrade times, we analyse the prices for both sets of stocks over the same periods.

Method

Like many financial time series the intertrade times (ITT) are inhomogeneous and nonstationary, with statistical properties changing with time, e.g. ITT data exhibit trends superposed on a pattern of daily activity [24]. While ITT fluctuate in an irregular and complex manner on a trade-by-trade basis, empirical observations reveal that periods of inactive trading are often followed by periods of more active trading (Fig. 1). Such patterns can be seen at scales of observation ranging from minutes to months, suggesting that there may be a self-similar, fractal structure in the temporal organisation of intertrade times, independent of the average level of trading activity of a given stock [24].

To probe for scale-invariant features in the fluctuations of intertrade times, we apply the detrended fluctuation analysis (DFA) method, which has been shown to detect and accurately quantify long-range power-law correlations embedded in noisy non-stationary time series with polynomial trends [25]. We choose this method because traditional techniques such as power spectral, autocorrelation and Hurst analyses are not suited to nonstationary data [26]. The DFA method (DFA-1) quantifies the root-mean-square fluctuations $F(n)$ of a signal at different time scales $n$, after accounting for nonstationarity in the data by subtracting underlying polynomial trends of order $(l−1)$. A power-law functional form $F(n)\propto n^\alpha$ indicates self-similarity and fractal scaling in the ITT time series. The scaling exponent $\alpha$ quantifies the strength of correlations in the ITT fluctuations: if $\alpha=0.5$ there are no correlations, and the signal is uncorrelated random noise; if $\alpha<0.5$ the signal is anti-correlated, meaning that large values are more likely to be followed by small values; if $\alpha>0.5$ there are positive correlations and the signal exhibits persistent behaviour, where large values are more likely to be followed by large values and small values by small values. The higher the value of $\alpha$, the stronger the correlations. The DFA method avoids the spurious detection of apparent long-range correlations that are an artifact of polynomial trends and other types of nonstationarities [27–30].

Results

We find that the ITT series for all stocks on both markets exhibit long-range power-law correlations over a broad range of time scales, from several trades to hundreds of thousands of trades, characterised by a scaling exponent $\alpha>0.5$ (Fig. 2 and Fig. 3). For all stocks on both markets we observe a crossover in the scaling curve $F(n)$ from a scaling regime with a lower exponent $x_1$ over time scales less than a trading day, to a scaling regime with an exponent $x_2>x_1$ (stronger positive correlations) over time scales from days to almost a year.

Further, we find that this crossover is systematically more pronounced for NYSE stocks compared to NASDAQ stocks (Fig. 2 and Fig. 3). Characterising ITT fluctuations over time scales less than a day, we find that NASDAQ stocks exhibit statistically stronger correlations than NYSE stocks as indicated by Student’s $t$-test ($t=25.28$, $p<10^{-61}$), with significantly higher average value of the exponent $x_1^{ITT,CPQ}=0.75\pm0.04$ (group mean $\pm$ std. dev.)
as compared to $\alpha_{ITT_{NYSE}} = 0.62 \pm 0.03$ (Fig. 3). In contrast, over time horizons above a trading day, we find that the correlation properties of ITT on both markets are statistically similar ($t = 2.27$, $p = 0.03$), with average scaling exponent $\alpha_{ITT_{NASDAQ}} = 0.85 \pm 0.08$ comparable with $\alpha_{ITT_{NASDAQ}} = 0.87 \pm 0.09$ (Fig. 3). Values for the scaling exponents $\alpha_{ITT}$ and $\alpha_{ITT}$ for the companies on the NYSE and NASDAQ markets are shown in Table 1 and Table 2 respectively.

We next investigate how the correlation properties of ITT depend on the average level of trading activity, and if this dependence differs with market structure. Since both sets of a hundred stocks that we study on the NYSE and NASDAQ markets encompass a range of average trading activity spanning over two decades, we split both sets into six subsets with matching average ITT ($\bar{ITT}$) and approximately equal numbers of stocks in each subset (Fig. 3a,b). Within each market we find that over time scales less than a day, the correlation exponent $\alpha_{ITT}$ characterising the trading dynamics is larger for stocks with higher trading activity (lower $\bar{ITT}$) and correspondingly higher market capitalisation (Fig. 3a,b and Fig. 4a).

The systematically higher values of $\alpha_{ITT}$ for NYSE stocks compared to NASDAQ stocks as compared to $\alpha_{ITT_{NYSE}} = 0.62 \pm 0.03$ (Fig. 3). In contrast, over time horizons above a trading day, we find that the correlation properties of ITT on both markets are statistically similar ($t = 2.27$, $p = 0.03$), with average scaling exponent $\alpha_{ITT_{NASDAQ}} = 0.85 \pm 0.08$ comparable with $\alpha_{ITT_{NASDAQ}} = 0.87 \pm 0.09$ (Fig. 3). Values for the scaling exponents $\alpha_{ITT}$ and $\alpha_{ITT}$ for the companies on the NYSE and NASDAQ markets are shown in Table 1 and Table 2 respectively.

We then compare the scaling behaviour of ITT for each subset of NASDAQ stocks with the corresponding subset of NYSE stocks with matching $\bar{ITT}$. We find that for each subset the average correlation exponent $\alpha_{ITT}$ for the NASDAQ stocks is significantly higher compared to the NYSE stocks (all $p$ values $< 10^{-13}$, as compared to $\alpha_{ITT_{NYSE}} = 0.62 \pm 0.03$ (Fig. 3). In contrast, over time horizons above a trading day, we find that the correlation properties of ITT on both markets are statistically similar ($t = 2.27$, $p = 0.03$), with average scaling exponent $\alpha_{ITT_{NASDAQ}} = 0.85 \pm 0.08$ comparable with $\alpha_{ITT_{NASDAQ}} = 0.87 \pm 0.09$ (Fig. 3). Values for the scaling exponents $\alpha_{ITT}$ and $\alpha_{ITT}$ for the companies on the NYSE and NASDAQ markets are shown in Table 1 and Table 2 respectively.

We next investigate how the correlation properties of ITT depend on the average level of trading activity, and if this dependence differs with market structure. Since both sets of a hundred stocks that we study on the NYSE and NASDAQ markets encompass a range of average trading activity spanning over two decades, we split both sets into six subsets with matching average ITT ($\bar{ITT}$) and approximately equal numbers of stocks in each subset (Fig. 3a,b). Within each market we find that over time scales less than a day, the correlation exponent $\alpha_{ITT}$ characterising the trading dynamics is larger for stocks with higher trading activity (lower $\bar{ITT}$) and correspondingly higher market capitalisation (Fig. 3a,b and Fig. 4a). Surprisingly, this dependence persists also for $\alpha_{ITT}$, characterising the dynamics over much longer time scales, ranging from days to months (Fig. 4b). For NYSE stocks we find a logarithmic dependence of $\alpha_{ITT}$ and $\alpha_{ITT}$ on $\bar{ITT}$ (Fig. 4b). For NASDAQ stocks we find a logarithmic dependence of $\alpha_{ITT}$ and $\alpha_{ITT}$ on $\bar{ITT}$ (Fig. 4b). For NASDAQ stocks we find a logarithmic dependence of $\alpha_{ITT}$ and $\alpha_{ITT}$ on $\bar{ITT}$ (Fig. 4b). For NASDAQ stocks we find a logarithmic dependence of $\alpha_{ITT}$ and $\alpha_{ITT}$ on $\bar{ITT}$ (Fig. 4b). For NASDAQ stocks we find a logarithmic dependence of $\alpha_{ITT}$ and $\alpha_{ITT}$ on $\bar{ITT}$ (Fig. 4b).
there is no systematic difference in the scaling behaviour of ITT that is more pronounced for NYSE stocks, and (ii) stronger correlations over intraday time scales of NASDAQ stocks with higher values for $\alpha_{1}^{\text{ITT}}$ compared to NYSE stocks, support our hypothesis that market structure affects the dynamics of transaction timing. However, more established companies listed on the NYSE may be subject to different trading patterns when compared with the younger and more rapidly growing companies on the NASDAQ. To verify that the stronger correlations in ITT over time scales less than a day for NASDAQ stocks are indeed due to market structure, we ask if the scaling properties of ITT systematically change for companies that transfer from the NASDAQ to the NYSE. In particular, we investigate the trading dynamics of ten companies that moved from the NASDAQ to the NYSE around the end of 1994 and the beginning of 1995 (Table 3). For each company, we analyse the ITT time series while the company was registered on the NASDAQ, and then repeat the analysis when the company was on the NYSE.

For all ten companies we find a significant change in the scaling properties of intertrade times: a marked decrease in the strength of the power-law correlations within a trading day (lower $\alpha_{1}^{\text{ITT}}$) associated with the transfer from the NASDAQ to the NYSE (average difference $\Delta \alpha_{1}^{\text{ITT}} = 0.13 \pm 0.03$; Fig. 5b). There is however, no corresponding systematic change in the correlations over time scales above a trading day (average difference $\Delta \alpha_{2}^{\text{ITT}} = 0.03 \pm 0.08$; Fig. 5c), consistent with our findings of statistically similar values of scaling exponent $\alpha_{2}^{\text{ITT}}$ for the two groups of one hundred stocks registered on the NYSE and NASDAQ (Fig. 2 and Fig. 3). Thus, our results indicate that market structure impacts not only trading dynamics on a trade-by-trade basis [19], but also the fractal temporal organisation of trades over time scales from a few seconds up to a day. The presence of stronger intraday correlations in transaction timing for NASDAQ stocks may be attributed to the multiplicity of dealers (ranging from 2 to 50 per stock during 1994 [11]) and electronic methods of trading (Electronic Communication Networks and the Small Order Execution System [7], allowing the NASDAQ to efficiently absorb fluctuations in trading activity in almost real time [5]. In contrast, for each stock on the NYSE, while there is the electronic SuperDOT routing system, each order has to be exposed to and compared with outstanding orders, as the single NYSE specialist finds the best bid to match an offer with [6]. This may lead to interruptions in the execution of a rapid succession of trades on the NYSE, resulting in weaker correlations in intertrade times within a trading day.

On the other hand, our finding of stronger power-law correlations for both markets over time horizons from a trading day to several months ($\alpha_{2}^{\text{ITT}}>\alpha_{2}^{\text{ITT}}$) suggests that investors' behaviour is more coherent over longer time scales, as information driving trading activity takes time to disseminate. Moreover, this can account for the similar values of $\alpha_{2}^{\text{ITT}}$ for subsets of NYSE and NASDAQ stocks with matched $\text{ITT}$ (Fig. 4b), since news and information driving trading activity are exogenous to market structure.

Finally, we investigate if the market-mediated differences in long-range power-law correlations in ITT translate into differences in the scaling behaviour of price fluctuations of stocks registered on the NASDAQ and NYSE markets. To this end, in parallel with ITT we analyse the absolute price returns for each company in our

Since for both NYSE and NASDAQ stocks we have chosen companies representing eleven industry sectors with a broad range of market capitalisations and average levels of trading activity spanning over more than two decades, our findings of (i) a crossover in the scaling behaviour of ITT that is more pronounced for NYSE stocks, and (ii) stronger correlations over intraday time scales of NASDAQ stocks with higher values for $\alpha_{1}^{\text{ITT}}$ compared to NYSE stocks, support our hypothesis that market structure affects the dynamics of transaction timing.
database for both markets. For all stocks we observe a crossover at a trading day in the scaling function $F(n)$ of price fluctuations [33,24], from weaker to stronger correlations, corresponding to the crossover we observe for intertrade times. In addition we find that over time scales less than a day, stocks with stronger correlations in ITT exhibit stronger correlations in absolute price returns (Fig. 6a), as indicated by Pearson’s test ($r = 0.9, p < 10^{-68}$). In particular, we find that the stronger correlations in ITT associated with the NASDAQ market structure ($\sigma_{1, ITT_{NASDAQ}}$), are accompanied by stronger correlations in price fluctuations ($\sigma_{1, RET_{NASDAQ}} > \sigma_{1, RET_{NYSE}}$) over time scales within a trading day (Fig. 6a).

We also find evidence of a positive relationship between correlations in ITT and correlations in price fluctuations over time scales larger than a trading day for NASDAQ stocks (Pearson’s test shows statistically significant correlation between $\sigma_{1, ITT_{NASDAQ}}$ with $\sigma_{1, RET_{NASDAQ}}$ with $r = 0.64$, $p < 10^{-12}$; Fig. 6b). In contrast, there is no corresponding positive relationship between $\sigma_{1, ITT_{NASDAQ}}$ with $\sigma_{1, RET_{NYSE}}$ for NYSE stocks (Pearson’s test: $r = 0.17, p = 0.1$), suggesting a weaker coupling between trading dynamics and price formation under the NYSE market structure, over time horizons above a trading day. While previous work has suggested that bursts of trading activity have an instantaneous impact on stock prices [19,34], our results show that the interaction between trading times and price formation is more complex, where scale invariant temporal patterns in ITT are linked with scaling features of price fluctuations over a broad range of time scales.

We then test whether long-range correlations in ITT are also linked with stock price volatility. Previous studies have reported higher price volatility for NASDAQ stocks compared to NYSE stocks [4,9,10]. We find a positive relationship, with stronger correlations in ITT over time scales less than a day related to higher daily volatility $\sigma_{RET}$ (Pearson’s test: $r = 0.73$, $p < 10^{-31}$; Fig. 6c). Further, we find that the NASDAQ stocks have higher $\sigma_{1, ITT}$ and correspondingly higher $\sigma_{RET}$ compared to NYSE stocks (Fig. 6c). This relationship may appear to follow from our observation that $\sigma_{1, ITT}$ depends on $\sigma_{1, RET}$ (Fig. 4a), and previous studies which connect price volatility with periods of high transaction rates [16,35]. However, for the stocks in our database (Tables 1 and 2), we find no correlation between $\sigma_{RET}$ and average level of trading activity as measured by $\sigma_{1, ITT}$ (Pearson’s test: $r = 0.01, p = 0.36$; Fig. 6d). Thus the relationship between $\sigma_{1, ITT}$ and $\sigma_{RET}$ suggests that information contained in the microscopic temporal structure of ITT is carried over a range of scales to impact daily price volatility.

Discussion

Understanding the statistical properties of intertrade times and the related underlying mechanism is crucial for the development of more realistic models not only of the flow of transactions [36–38], but more importantly to elucidate (i) the relation between intertrade time dynamics and stock price formation [16,18,39–41], and (ii) how the process of stock price formation is influenced by market structure. In that context, several prior studies have focused not only on the correlation properties, but also on nonlinear features of intertrade times, and on the functional form of their probability distribution. Early studies reported stretched exponential distributions for intertrade times based on data from a single actively-traded stock over a short period of a few months [16,17], or power-law tailed distributions for rarely-traded 19th century stocks [42] and eurobonds traded in 1997 [43]. While
some of these studies have also considered autocorrelations in intertrade times, they have not identified the functional form of these correlations and whether they are persistent or anti-persistent. A first systematic empirical study based on 30 frequently-traded US stocks over a long period of several years [24] has (i) reported long-range power-law correlations of persistent type with a characteristic crossover to a superdiffusive behavior at time scales above a trading day, and (ii) identified a Weibull functional form for the distribution of intertrade times. In a follow up study based on a different group of US stocks [30], the Weibull functional form was also considered a good fit for the intertrade time distribution, with the Tsallis q-exponential form as an alternative. Further investigations considering the intertrade dynamics of a group of frequently-traded Chinese stocks have shown that the Weibull distribution outperforms the Tsallis q-exponential for more than 90.5% of the data [20]. The long-range power law correlations in intertrade times initially reported for US stocks [24] were also observed for liquid stocks on the Shanghai Stock Exchange [22]. Our results based on 100 NASDAQ and 100 NYSE stocks confirm the presence the long-range power law correlations. The results of these studies, which focus on different markets and different time periods, confirm that the Weibull distribution and long-range power law correlations are stable characteristics of intertrade time dynamics across markets and temporal time scales. Interestingly, similar characteristics were recently reported for commodity dynamics of ancient Babylon (463–72 B.C), and medieval and early modern England (1209–1914 A.D.) markets [44].

It has been recently hypothesized [36] that the dynamics of intertrade times maybe governed by a priority decision-based queuing mechanism [45,46]. This hypothesis, however, does not appear plausible. First, the priority queuing process proposed in [45] leads to power law distributions for the timing between events, which has been rejected for intertrade times [20,38]. Second, this queuing process does not generate long-term correlations, contrary to empirical findings for intertrade times of stocks reported in [20,22,24], and in the current study comparing stocks on different markets. Moreover, the activity pattern of a single stock broker is not adequately described by a power law, but rather by a power law with a stretched exponential tail [46], which is actually the functional form of the Weibull distribution [24]. Further, it is unlikely that the priority decision-based queuing process underlies stock market operations, since market agents treat all orders for stock transactions with the same priority no matter how big or small the order, because the objective of market agents is to execute all orders as soon as possible. For this reason, each stock transaction is a minimal time event realization resulting from the competition of a number of market agents with different reaction times—the statistics of minimal events derived from multiple realizations are described by Weibull distributions. Thus, the process of stock market operations is markedly different from the processes governing the dynamics of other human activities, such as web browsing or email exchange that are based on priority queuing [45,46]. Furthermore, in contrast to priority decision-based processes, intertrade dynamics exhibit nonlinear (multifractal) properties, as first empirically identified in [24] and later confirmed in the framework of multifractal random walks [36].

To summarize, this is the first large empirical study to investigate intertrade times comparing 200 stocks registered on the NYSE and NASDAQ markets representing diverse sectors of the economy, where all stock transactions over a period of four years are included (Table 1 and 2, Figure 2 and Figure 3). This is also the first study to examine changes in the trading dynamics of stocks of companies that moved from one market to the other (Table 2 and Figure 5).
We report that trading dynamics of company stocks are characterized by a scale-invariant temporal organisation of intertrade times which is significantly different for stocks registered on the NYSE and the NASDAQ, indicating that market structure influences the correlation properties of transaction timing. Specifically, we find that intertrade times are more strongly correlated for NASDAQ stocks, when data are analysed over time scales within a trading day, and that this difference is independent of the average level of trading activity of the companies (Figures 2, 3 and 4). In contrast, on time scales above a trading day there is no significant difference in the long-range correlations of companies on the two markets.

Investigating a group of companies that transferred from the NASDAQ to the NYSE, we find that intertrade times exhibit significantly stronger power-law correlations over scales from seconds to a trading day while the companies are on the NASDAQ (Figure 5). These findings suggest that market structure impacts trading dynamics, not only on a trade-by-trade basis, but over a broad range of time scales. In addition, our results imply that within a trading day the NASDAQ market structure may be more efficient than the NYSE market structure in absorbing rapid variations in trading activity in response to investors’ demand [47].

In contrast, on scales above a trading day our results suggest a more coherent behavior of market agents in response to events on

Figure 6. Relation between correlations in intertrade times and stock price dynamics. (a) Dependence of exponent $\alpha_1^{\text{ITT}}$ characterising power-law correlations in absolute logarithmic price return fluctuations, on correlation exponent $\alpha_1^{\text{RET}}$ characterising intertrade times within a trading day. Data represent one hundred NYSE (Table 1) and one hundred NASDAQ (Table 2) stocks. We calculate price returns over 1-minute intervals and $\alpha_1^{\text{ITT}}$ over time scales from 8 to 180 minutes (≈ half a trading day, which is 390 minutes). The positive relationship between $\alpha_1^{\text{ITT}}$ and $\alpha_1^{\text{RET}}$ indicates that stronger correlations in ITT are coupled with stronger correlations in price fluctuations. This finding suggests that price fluctuations are not merely a response to short-term bursts of trading activity [34,16]: rather the fractal organisation of price fluctuations over a broad range of time scales is linked to the observed underlying scaling features in the series of intertrade times. (b) Strong relationship between correlations in ITT and price fluctuations over time scales larger than a trading day for NASDAQ stocks. In contrast, there is no corresponding positive relationship for NYSE stocks. This suggests a weaker coupling between trading dynamics and price formation under the NYSE market structure, over time horizons above a trading day. Dependence of stock price volatility $\sigma^{\text{RET}}$ on (c) the correlation exponent $\alpha_1^{\text{ITT}}$ and (d) the average value of ITT for the same stocks as in (a). We calculate $\sigma^{\text{RET}}$ as the standard deviation of daily logarithmic price returns over six-month periods throughout the entire record of each stock. Our results show no strong dependence between stock price volatility $\sigma^{\text{RET}}$ and average level of trading activity, rather the volatility appears sensitive to the strength of the temporal correlations in ITT. These findings suggest that scale-invariant features in transaction times may play an important role in price formation. Furthermore, both dynamic and static properties of stock prices appear to be influenced by market-specific features in transaction timing: stronger power-law correlations in ITT (higher values of $\alpha_1^{\text{ITT}}$) for NASDAQ stocks are matched by stronger power-law correlations in price fluctuations (higher values of $\alpha_1^{\text{RET}}$) and higher volatility ($\sigma^{\text{RET}}$), compared with NYSE stocks.

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larger time scales, thus leading to stronger correlations in intertrade times for the companies on both markets.

Importantly, we also uncover a strong dependence between the scale-invariant features of intertrade times and stock price fluctuations: stocks with stronger correlations in their intertrade times also exhibit stronger correlations in their absolute price returns (Figure 6), indicating an influence of trading activity patterns on the dynamics of price formation. Furthermore, we show that within a trading day absolute price returns, like intertrade times, are more strongly correlated for stocks registered on the NASDAQ market (Figure 6a), and that higher price volatility on the NASDAQ is coupled with stronger correlations in intertrade times (Figure 6c). These findings suggest that market-mediated differences in transaction timing translate into differences in the scaling behavior of stock prices over a broad range of time scales.

Finally, our results do not support the hypothesis of a universal behavior in stock dynamics that is independent of individual company characteristics. In contrast to earlier studies reporting identical scaling exponents for stock price returns, volume and company characteristics, our findings show a strong dependence of the scaling behavior of intertrade times on the market capitalization and the average frequency of trading of individual companies (Figure 2 and Figure 3), as well as on the market structure where the companies are traded. Recent studies [32,53] have also demonstrated that stock price returns and volume do not exhibit universal behavior, but rather depend on market capitalization. Our results show that this universality does not hold also because trading dynamics are strongly influenced by market-specific trading operations and market structure. Our results may have implications for the use of transaction timing patterns in the prediction of prices and risk management on different stock markets. These observations are of interest in the context of the continuing process of optimizing market structure to maintain the efficiency and competitiveness of U.S. stock markets [1].

Author Contributions
Conceived and designed the experiments: PCChI AY. Performed the experiments: PCChI AY. Analyzed the data: PCChI AY. Contributed reagents/materials/analysis tools: PCChI AY. Wrote the paper: PCChI AY.