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Autocorrelation and partial price adjustment[☆]

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ABSTRACT

Stock return autocorrelation contains spurious components—the nonsynchronous trading effect (NT) and bid–ask bounce (BAB)—and genuine components—partial price adjustment (PPA) and time-varying risk premia (TVRP). We identify a portion that can unambiguously be attributed to PPA, using three key ideas: theoretically signing and/or bounding the components; computing returns over disjoint subperiods separated by a trade to eliminate NT and greatly reduce BAB; and dividing the data period into disjoint subperiods to obtain independence for statistical power. Analyzing daily individual and portfolio return autocorrelations in sixteen years of NYSE intraday transaction data, we find compelling evidence that PPA is a major source of the autocorrelation.

1. Introduction

One of the most visible stylized facts in empirical finance is the autocorrelation of stock returns at fixed intervals (daily, weekly, monthly). This autocorrelation presents a challenge to the main models in continuous-time finance, which rely on some form of the random walk hypothesis. Consequently, there is an extensive literature on stock return autocorrelation; it occupies four segments totaling 55 pages of Campbell et al. (1997). The results of this literature have been, however, inconclusive; see the literature review in Section 2 of Anderson et al. (2012).

This paper presents a comprehensive analysis of daily stock return autocorrelation on the New York Stock Exchange (NYSE). Our goal is to show that simple methods, applied to intraday data, allow us to resolve the questions concerning *daily return autocorrelation* left unanswered by the literature. Daily return autocorrelation has been attributed to four main sources: spurious autocorrelation arising from market microstructure biases, including the nonsynchronous trading effect (NT) (in which autocorrelations are calculated using stale prices) and bid–ask bounce (BAB), and genuine autocorrelation arising from partial

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price adjustment (PPA) (i.e., trade takes place at prices that do not fully reflect the traders' information, for example by traders strategically timing their trades as in Kyle, 1985) and time-varying risk premia (TVRP). The term “spurious” indicates that NT and BAB arise from microstructure sources which bias the autocorrelation tests. Even if the underlying securities price process were a geometric Brownian motion with constant drift, which has zero autocorrelation, the inclusion of microstructure bias makes the observed securities price process appear to be autocorrelated.

In this paper, we make use of three key ideas: signing and/or bounding the contributions of NT, BAB, and TVRP to stock return autocorrelation; eliminating NT by computing returns over disjoint return subperiods, separated by a trade; and measuring autocorrelation over disjoint time-horizon subperiods to obtain independence for statistical power. Using these three methods, we isolate a portion of the daily return autocorrelation which must come from PPA.

We examine Trade and Quote (TAQ) data from 1993 through 2008, broken into eight two-year time-horizon subperiods. In each subperiod, we select 1000 stocks representing the full spectrum of market capitalization on the NYSE; these 1000 stocks are classified into 10 groups of 100 stocks by market capitalization. We apply our three key ideas in various contexts to both individual stock and portfolio return autocorrelation.

For individual stock returns, we find that PPA must be an important source of the autocorrelation. PPA is systematically positive in the first half (1993–2000) of our data period and systematically negative in the second half (2001–2008). Positive PPA autocorrelation reflects slow price adjustment, while negative PPA autocorrelation reflects overshooting.

Our portfolio return autocorrelation results closely parallel the individual stock return autocorrelation results. PPA is the major source of daily return autocorrelation in portfolios. SPDRs, an Exchange-Traded Fund (ETF) based on the Standard and Poor's 500 (S&P 500) Index, exhibits negative return autocorrelation, which cannot be explained by BAB and therefore must reflect PPA. Past returns of SPDRs predict future returns of individual stocks, which must reflect PPA.

For both individual stock and portfolio returns, PPA and total autocorrelation vary in sign over our sixteen-year data period, but have consistent signs over subperiods lasting several years. For both, a pronounced shift from positive to negative occurred over the course of our data period. We conjecture that the sign of PPA is determined by the prevalence of momentum traders in the market and by the relative importance of high-frequency trading.

The remainder of this paper is organized as follows. Section 2 details our methodology, null hypotheses, and findings. Section 3 concludes.

2. Methodology, hypotheses, and findings

2.1. Three key ideas

2.1.1. Key idea 1: sign and/or bound the sources of autocorrelation theoretically

The first key idea in this paper is to theoretically sign and/or bound the various sources of autocorrelation, to draw inferences about the source from the sign of the observed autocorrelation.

- NT is negative for individual stock returns, and is generally positive for portfolio returns.[1] We argue that autocorrelations computed from *open-to-close* returns[2] are free of NT.
- BAB is negative for both individual stock and portfolio returns, and is generally considered to be very small for portfolio returns. We argue that open-to-close returns are essentially free of BAB. Thus, we shall assume that for all but one of our portfolio tests, the contribution of BAB to portfolio return autocorrelation is zero.
- PPA can be either positive or negative for both individual stock and portfolio returns.
- TVRP is positive for both individual stock and portfolio returns. Anderson (2011) shows that TVRP is sufficiently small that it can be ignored in the setting considered here: daily return autocorrelation tests on a two-year time-horizon subperiod.[3]

Consequently, in the discussion of our tests, we shall assume there are only three sources (NT, BAB, and PPA) for daily return autocorrelation of individual stocks, and only two sources (NT and PPA) for daily portfolio return autocorrelation. If we find

[1] As noted by Lo and MacKinlay (1990), NT arises from measurement error in calculating stock returns. If an individual stock does not trade on a given day, its daily return is reported as zero. [Because our primary focus is separating PPA from NT, we need to use intraday transaction data, and thus we use the NYSE TAQ dataset. The Center for Research in Security Prices (CRSP) dataset reports the average of the final bid and ask quotes as the “closing price” so that returns calculated from CRSP data will generally not be zero on no-trade days.] Think of the “true” price of the stock being driven by a positive (negative) drift component, the equilibrium mean return, plus a daily mean-zero volatility term, with the reported price being updated only on those days on which trade occurs. On days on which no trade occurs, the reported return is zero, which is below (above) trend; on days on which trade occurs after one or more days without trade, the reported return represents several days' worth of trend; this results in spurious negative autocorrelation. Even if a stock does trade on a given day, the reported “daily closing price” is the price at which the last transaction occurred, which might be several hours before the market closed. Thus, a single piece of information that affects the underlying value of stocks i and j may be incorporated into the reported price of i today because i trades after the information is revealed, but not incorporated into the reported price of j until tomorrow because j has no further trades today, resulting in a positive cross-autocorrelation between the prices of i and j.

[2] The open-to-close return of a stock is defined as the closing price today, minus the opening price today, divided by the opening price today. The conventional daily return is defined as the closing price today, minus the closing price yesterday, divided by the closing price yesterday.

[3] If the expected return on a security varies over the time-horizon subperiod, it results in positive autocorrelation that standard autocorrelation tests cannot distinguish from PPA. The bias resulting from TVRP in the p-values in hypothesis tests depends in a complex way on the return period, the time horizon over which the autocorrelations are calculated, and the variability of the risk premium over the time horizon. This bias may be big enough to matter in empirical settings other than the one considered here. See Anderson (2011) for details.

Table 1
Signs of conventional daily return autocorrelation from various sources. BAB denotes bid–ask bounce, NT the nonsynchronous trading effect, PPA partial price adjustment, and TVRP time-varying risk premium.

Source	Individual stock	Portfolio
BAB	−	−/0
NT	−	+
PPA	+/−	+/−
TVRP	+	+

statistically significant positive autocorrelation in individual stock returns, it can only come from PPA. If we find statistically significant negative autocorrelation in portfolio returns, it can only come from PPA. The signs are summarized in Table 1.

2.1.2. Key idea 2: eliminate NT by computing returns over disjoint return subperiods, separated by a trade

The second key idea in this paper is to study stock returns over *disjoint* time intervals where a *trade occurs between the intervals* to eliminate NT. More formally, we study the correlation of stock returns over intervals $[s,t]$ and $[u,v]$ with $s < t \leq u < v$ such that the stock trades at least once on the interval $[t,u]$. We apply this idea to derive tests in a number of different situations. Because these correlation calculations do not make use of stale prices, NT is, *by definition*, eliminated; if the correlation turns out to be nonzero, there must be a source, other than NT, for the correlation. This conclusion does not depend on any particular story of how the use of stale prices results in spurious correlation.

An important example of this key idea is the study of open-to-close returns. The open-to-close return of stock i on day d is $r_{s_it_ii}$, where s_i and t_i are the times of the first and last trades of the stock on day d. We compute the correlation $\rho(r_{s_it_ii}, r_{u_iv_ii})$, where u_i and v_i are the times of the first and last trades on day $d+1$. Note that $s_i < t_i < u_i < v_i$, so NT is eliminated. As noted above, TVRP in this empirical setting is sufficiently small that it can be ignored.

BAB arises in conventional daily return autocorrelation because the correlation considered is $\rho(r_{q_it_ii}, r_{t_iv_ii})$, where q_i is the time of the last trade prior to day d. Note that the end time in calculating $r_{q_it_ii}$ is the same as the starting time in calculating $r_{t_iv_ii}$, resulting in negative autocorrelation, as explained in Roll (1984); Roll's model assumes that at each trade, the toss of a fair coin determines whether the trade occurs at the bid or ask price. In the calculation of the open-to-close autocorrelation, the end time t_i of the first interval is different from the starting time u_i of the second interval. Moreover, the trades at t_i and u_i are different trades, so the coin tosses for these trades are independent; if we apply Roll's model to this situation, the autocorrelation resulting from BAB is zero.[4]

Thus, we assume that BAB does not contribute to autocorrelation in open-to-close returns of individual stocks or portfolios. Since NT and BAB are eliminated in open-to-close returns, and TVRP is too small to affect our tests, and autocorrelation we find in open-to-close returns must come from PPA.

2.1.3. Key idea 3: measure autocorrelation over disjoint time-horizon subperiods to obtain independence for statistical power

The third key idea is to divide the data period into disjoint time-horizon subperiods, and note that under the assumption that the theoretical autocorrelation is zero, the sample return autocorrelations within disjoint time-horizon subperiods are independent; hence, we may derive tests using the binomial distribution.

This idea is applied in two settings. In the first setting, we compute a single sample autocorrelation in each subperiod; in one case, we compute the average of individual stock return sample autocorrelations over each subperiod, while in another case, we compute the sample portfolio return autocorrelation over each subperiod. We count the number of time-horizon subperiods in which the single autocorrelation value is statistically significant at the two-sided (+/−) 5% level, and use the binomial distribution to compute p-values. We do tests over the eight two-year time-horizon subperiods within 1993–2008; we also break our data period into two halves (1993–2000 and 2001–2008) and break each half into four two-year time-horizon subperiods. The p-values for the binomial distribution are listed in Table 2.

In the second setting, we apply the binomial distribution to counts of stocks with statistically significant return autocorrelations in each of the time-horizon subperiods. We consider separately positive only (+), negative only (−), and positive or negative (+/−) rejections using a one-sided 2.5% rejection criterion for + and for −, and a symmetric 5% rejection criterion for +/−. If the correlation tests were independent across firms, the number of rejections would have the binomial distribution. If the collection $\{r_{s_it_ii} : i = 1, \ldots, I\}$ were a family of independent random variables, then X, the number of firms for which the zero-correlation hypothesis is rejected at the 5% (2.5%) level, would be binomially distributed, as $B(I,0.05)$ ($B(I,0.025)$), which has mean $0.05I$ ($0.025I$) and standard deviation $\sqrt{(.05)(.95)I}$ ($\sqrt{(.025)(.975)I}$). Since returns are not independent across stocks, X will not be binomial. The standard deviation of X is not readily ascertainable, and is likely higher than that of the binomial. However, the failure of independence does not change the mean of X, so X is a nonnegative, integer-valued, random variable with mean $0.05I$ ($0.025I$).

In all of these tests, there are $I = 100$ firms, so X has mean $\mu = 5$ or $\mu = 2.5$. Since X is nonnegative, $P(X \geq \alpha\mu) \leq 1/\alpha$ for every $\alpha \geq 1$.[5] Suppose that we compute X in each of n disjoint time-horizon subperiods. This provides us with n independent observations of

[4] If we extend Roll's model to multiple stocks, and assume the coin tosses are independent across stocks, the autocorrelation and cross-autocorrelation of open-to-close stock returns are zero. Relaxing the independence assumption results in slightly negative autocorrelation and cross-autocorrelation of open-to-close returns.

[5] This is Markov's Inequality, the linear version of the Chebychev's Inequality; see Markov's Inequality in www.wikipedia.org.

Table 2
Binomial p-values combining two-year time-horizon subperiod results, 5% two-sided tests in each subperiod. In each subperiod, we determine whether or not a hypothesis is rejected by a 5% two-sided test. We then count the number of subperiods in which the hypothesis is rejected, and compute the p-value from the binomial distribution. For example, the probability that a correct hypothesis is rejected in two of four subperiods is 0.0140.

Number of rejections	p-Value (four subperiods)	p-Value (eight subperiods)
0	1.0000	1.0000
1	0.1855	0.3366
2	0.0140	0.0572
3	0.0005	0.0058
4	6.25×10^{-6}	0.0004
5	–	1.54×10^{-5}
6	–	4.01×10^{-7}
7	–	5.98×10^{-9}
8	–	3.91×10^{-11}

X; let $X_1, \ldots, X_n$ be the order statistics, i.e., X_1 is the smallest observation, X_2 the second smallest, and so forth. Then using the binomial distribution, for every $\alpha \geq 1$, $P(X_1 \geq \alpha\mu) \leq 1/\alpha^n$ and $P(X_2 \geq \alpha\mu) \leq 1/\alpha^n + n(1 - 1/\alpha)/\alpha^{n-1} = (n\alpha - (n-1))/\alpha^n$. Given particular realizations $x_1 \geq \mu$ and $x_2 \geq \mu$ of X_1 and X_2, we obtain p-values of $p_1 = 1/(x_1/\mu)^n$ for x_1 and $p_2 = (n(x_2/\mu) - (n-1))/(x_2/\mu)^n$ for x_2, respectively. The test for the kth order statistic X_k involves the combinatorial coefficient $n!\ /\ ((k-1)!(n-k+1)!)$ as well as the factor $(\mu/x_k)^{n-k+1}$, both of which grow rapidly with k. Thus, the power of the test for X_k declines rapidly with k, suggesting the test be based on X_1 alone. However, the test for X_1 can be strongly affected by a single outlier. In particular, if any single realization of X is less than μ, then $p_1 = 1$ and the null hypothesis will not be rejected. For these reasons, we adopt a combined test using the minimum of the p-values p_1 and p_2, rather than using the higher order statistics. Note that for any γ, $P(min\{p_1,p_2\} \leq \gamma/2) = P(2min\{p_1,p_2\} \leq \gamma) = P(p_1 \leq \gamma/2 \text{ or } p_2 \leq \gamma/2) \leq P(p_1 \leq \gamma/2) + P(p_2 \leq \gamma/2) = \gamma/2 + \gamma/2 = \gamma$. Thus, we compute $p_3 = 2min\{p_1,p_2\}$, the correct p-value for the combined test. Note that p_3 depends on μ and n.

As a robustness check, we also compute the average of the p-values across the time periods. Specifically, let $Y_1, \ldots, Y_n$ denote the n independent observations of X, in time order rather than order statistics. Since $P(\mu/Y_i \leq 1/\alpha) \leq 1/\alpha$ for all $\alpha \geq 1$, the unknown true distribution of $\min\{\mu/Y_i,1\}$ first-order stochastically dominates the distribution of a random variable $Z = \max\{\mu/n, U\}$, where U has the uniform distribution on [0,1]. We compute the statistic $p_4 = (\min\{\mu/Y_i,1\} + \ldots + \min\{\mu/Y_n,1\})/n$, and determine significance levels for this statistic using Monte Carlo simulation and the distribution of Z. The statistical significance is qualitatively similar using p_3 and p_4.

2.2. Autocorrelation tests

Testing each of our Null Hypotheses requires testing whether a correlation or a set of correlations is zero, positive, or negative. Our main analysis uses the Pearson correlation test. To ensure robustness, we also use the Andrews (1991) heteroskedasticity and autoregression consistent (HAC) covariance estimator, and the Kendall τ-test.

2.3. Data

We use TAQ data for the sixteen calendar years 1993–2008. The sample firms are obtained from NYSE-listed stocks through a conventional filtering process. For each two-year time horizon subperiod, we select 1000 common stocks to have market capitalization equally distributed from largest to smallest firms.[6] Descriptive statistics of our data are given in Table 3, which reflects the broad coverage of the totality of NYSE-listed stocks.

2.4. Individual stock returns

Previous studies of individual stock return autocorrelation have focused on the average autocorrelation of groups of firms, finding it to be statistically insignificant and usually positive (Chan (1993), Säfvenblad (2000)).[7] This finding does not rule out the possibility that some stocks exhibit positive autocorrelation and others exhibit negative autocorrelation, with the two largely canceling out when averaged over stocks. None of the previous studies analyzed the autocorrelation of individual stocks one by one. This is the focus of our analysis, because it allows us to test whether the autocorrelation arises from PPA; as a comparison to the previous literature, we also compute the average autocorrelation over groups of firms, segregated by firm size. We calculate the autocorrelation in two different ways: the conventional daily return autocorrelation, and the open-to-close return autocorrelation.

[6] A detailed description of our procedure for sampling firms is provided in Section 4 of Anderson et al. (2012).

[7] Llorente et al. (2002) and Boulatov et al. (2013) model the effect of PPA on autocorrelation. Both papers consider the effect of informed traders using their information slowly (as in Kyle (1985)). Llorente et al. (2002) argue that positive autocorrelation arises if speculative trading predominates over hedging. Using a variety of methodologies, Chordia and Swaminathan (2000), Llorente et al. (2002), and Connolly and Stivers (2003) find support for the partial price adjustment hypothesis; see also Brennan et al. (1993), Mech (1993), Badrinath et al. (1995), McQueen et al. (1996). In the model of Boulatov et al. (2013), the fundamental values of different securities are correlated. They find that the intensity of informed traders' strategies in a particular asset is positive in the signal for that asset and negative in the signal for the other assets, and show on pages 43–45 that this implies that a past increase (decrease) in the price of one asset predicts a future increase (decrease) in the price of other assets.

Table 3
Descriptive statistics of data. We use transaction data from TAQ database over the data period from January 4, 1993 to December 31, 2008, drawing separate samples of firms in each two-year subperiod. All statistics are first calculated in each of the eight two-year time-horizon subperiods, then averaged over the eight subperiods. See Anderson et al. (2012) for details of the sampling procedure.

Portfolio	No. of firms	Market capitalization (in mil. of dollars)			Daily *portfolio* returns[a]		Average daily trading volume (in shares)	Average time interval between the closing trade of individual stock and the closing trade of SPDRs (in s)	Average number of days on which trade occurs
		Mean	Min	Max	Mean (%)	Std. dev. (%)			
Smallest	100	166.2	96.0	241.6	0.056	1.191	95,470.3	1815.4	496.8
2	100	327.4	244.6	415.2	0.050	1.276	173,214.1	1072.6	501.6
3	100	507.7	416.8	611.4	0.049	1.237	227,023.4	768.5	502.9
4	100	748.0	614.5	901.5	0.035	1.227	278,469.4	615.0	503.2
5	100	1093.8	905.4	1312.0	0.046	1.194	394,488.1	443.8	503.6
6	100	1581.3	1315.1	1904.7	0.039	1.136	481,259.1	317.9	503.7
7	100	2394.2	1911.9	2985.2	0.038	1.165	707,722.2	218.7	503.7
8	100	4076.4	3001.5	5558.9	0.042	1.167	1,003,812.0	165.0	503.8
9	100	8314.0	5617.0	12,130.5	0.042	1.145	1,677,393.0	122.9	503.7
Largest	100	41,587.5	12,3111.4	276,262.5	0.038	1.185	4,268,534.0	84.1	503.8

[a] Denotes the statistics of portfolios, not the average of individual firms of each group.

2.4.1. Conventional daily return autocorrelation

For each firm, we calculate the daily return on each day in the conventional way: the closing price on day d, minus the closing price on the last day prior to day d on which trade occurs, divided by the closing price on the last day prior to day d on which trade occurs. When we compute individual stock returns in the conventional way, NT and BAB are both present, and both generate negative autocorrelation. *Null Hypothesis I* is that the *average* daily return autocorrelation is zero in each firm-size group in each of our eight two-year time-horizon subperiods; we test this hypothesis by comparing the average sample daily return autocorrelation for each subperiod to the associated standard error. In each firm-size group and two-year time-horizon subperiod, we do a two-sided test with a 5% rejection criterion. Positive rejections can only come from PPA; negative rejections can arise from a combination of NT, BAB, and PPA.

Null Hypothesis I is rejected at the 1% level in all ten firm-size groups (0.1% level in eight of the ten groups); in addition, it is rejected in the first half of our data period at the 5% level in six of the ten firm-size groups, and in the second half of our data period at the 0.1% level in all ten firm-size groups. The significant autocorrelations are predominantly positive in the first half; these positive autocorrelations can come only from PPA. All but one of the significant autocorrelations in the second half are negative; these could come from any combination of NT, BAB, and PPA.[8]

Null Hypothesis II is that *every* firm's conventional daily return exhibits zero autocorrelation. For each firm, we test whether daily returns exhibit zero autocorrelation, in each of $n = 8$ disjoint two-year time-horizon subperiods, using $+$ and $-$ one-sided test with a 2.5% rejection criterion, as well as a $+/-$ two-sided test with a 5% rejection criterion. Positive rejections can only come from PPA; negative rejections could come from any combination of NT, BAB, and PPA. In each subperiod, the $+$ and $-$ tests correspond to $\mu = 2.5$, while the $+/-$ two-sided test corresponds to $\mu = 5$. Applying this test to 100 firms in each of the eight disjoint subperiods, we reject Null Hypothesis II if $p_3 < 0.05$. In the alternate test using p_4, the average of the p-values, we reject based on the values determined by our Monte Carlo simulation.

Table 4 reports our main results on individual stock conventional return autocorrelation: the tests for Null Hypothesis II. With autocorrelations calculated using the Pearson test, Null Hypothesis II is rejected at the 5% level or better for all firm size groups in the binomial test and at the 1% level or better for all firm size groups in the average of p-values test. The signs of the significant autocorrelations are mixed, with positive outnumbering negative in the first half of our data period, while the significant autocorrelations are overwhelmingly negative in the second half. As above, significant positive autocorrelations can only come from PPA, while significant negative autocorrelations reflect any combination of PPA, BAB, and NT.

2.4.2. Open-to-close return autocorrelation

As above in Section 2.1.2, we define the open-to-close return on day d as the price at the final trade on day d, minus the price at the first trade on day d, divided by the price at the first trade on day d. If a given stock does not trade, or has only one trade, on a given day, we drop the observation of that stock for that day from our dataset. If PPA makes no contribution to stock return autocorrelation, the theoretical autocorrelation of open-to-close returns on each stock must be zero.

As with the conventional daily return, we use one-sided $+$ and $-$ tests, and a two-sided $+/-$ test. *Null Hypothesis III* is that the *average* autocorrelation of open-to-close returns is zero in each of the eight two-year time-horizon subperiods in each group of stocks. The testing procedure and rejection criteria are identical to those for Null Hypothesis I. Rejection of Null Hypothesis III, whether positive or negative, implies that PPA contributes to stock return autocorrelation. As in the case of conventional returns, we also compute the average autocorrelations over the entire sixteen-year period.

[8] For brevity, we do not report the detailed results in a table; these may be found in Table 4 of Anderson et al. (2012).

Table 4

Autocorrelation of daily *individual* stock returns: conventional daily returns (Null Hypothesis II). We report the number of firms exhibiting positive (+), negative (−), and two-sided (+−) significant autocorrelation at the 2.5% one-sided (5% two-sided) levels. We report a *p*-value, p_3, derived from the first and second order statistics (minimum and second lowest) of the observations for the eight two-year time-horizon subperiods in 93–08, as well as for the four two-year time-horizon subperiods in 93–00 and 01–08. We also report p_4, the average of the *p*-values over the eight or four two-year time-horizon subperiods; p_4 is not itself a *p*-value, and significance levels are determined by Monte Carlo simulation. ***, **, and * denote significance at the 0.1%, 1%, and 5% levels. Pearson correlation tests are used in this table; results using the Andrews test and Kendall τ-test are reported in Panels B and C of Table A1 of Anderson et al. (2012).

Portfolio		Autocorrelation of daily *individual* stock returns: conventional daily returns								Binomial *p*-value			Average *p*-value		
		93–94	95–96	97–98	99–00	01–02	03–04	05–06	07–08	93–08	93–00	01–08	93–08	93–00	01–08
										p_3	p_3	p_3	p_4	p_4	p_4
Pearson correlation test															
S	+	12	13	31	19	31	14	6	5	0.0078**	0.0038**	0.1250	0.224**	0.153**	0.294
	−	26	38	15	20	10	14	20	45	0.0000***	0.0015**	0.0078**	0.133***	0.113**	0.152**
	+−	38	51	46	39	41	28	26	50	0.0000***	0.0006***	0.0027**	0.132***	0.117**	0.148**
2	+	26	22	45	17	18	7	3	7	0.0082**	0.0009***	0.6312	0.262**	0.103**	0.422
	−	16	18	6	15	18	26	17	38	0.0000***	0.0603	0.0009***	0.166***	0.220**	0.112**
	+−	42	40	51	32	36	33	20	45	0.0000***	0.0012**	0.0078**	0.144***	0.125**	0.163**
3	+	23	23	38	21	15	0	8	6	0.0222*	0.0004***	0.9766	0.287**	0.101**	0.474
	−	13	12	5	10	28	31	12	34	0.0008***	0.1250	0.0038**	0.200**	0.288	0.113**
	+−	36	35	43	31	43	31	20	40	0.0000***	0.0014**	0.0078**	0.151***	0.140**	0.163**
4	+	30	18	41	11	5	1	7	7	0.0703	0.0053**	1.0000	0.341	0.128**	0.554
	−	10	22	7	21	31	37	18	31	0.0005***	0.0325*	0.0007***	0.151***	0.210**	0.092***
	+−	40	40	48	32	36	38	25	38	0.0000***	0.0012**	0.0032**	0.139***	0.128**	0.151**
5	+	24	23	20	11	6	3	6	9	0.0222*	0.0053**	0.9645	0.314**	0.141**	0.486
	−	15	13	14	16	26	26	8	23	0.0001***	0.0027**	0.0191*	0.163***	0.173**	0.153**
	+−	39	36	34	27	32	29	14	32	0.0001***	0.0024**	0.0325*	0.180***	0.150**	0.211**
6	+	18	15	9	6	9	3	4	4	0.2701	0.0603	0.9645	0.420	0.250**	0.590
	−	5	16	12	23	16	18	8	24	0.0034**	0.1250	0.0191*	0.211**	0.243**	0.178**
	+−	23	31	21	29	25	21	12	28	0.0005***	0.0064**	0.0603	0.228**	0.197**	0.258**
7	+	21	14	18	7	7	4	3	6	0.2701	0.0325*	0.9645	0.378	0.198**	0.558
	−	13	18	11	14	11	15	10	33	0.0000***	0.0053**	0.0078**	0.182***	0.184**	0.180**
	+−	34	32	29	21	18	19	13	39	0.0010***	0.0064**	0.0438*	0.221**	0.178**	0.263
8	+	18	9	3	4	5	3	2	8	1.0000	0.9645	1.0000	0.565	0.469	0.661
	−	7	11	8	15	4	18	11	33	0.0082**	0.0325*	0.1718	0.266**	0.266	0.267
	+−	25	20	11	19	9	21	13	41	0.0181*	0.0854	0.1905	0.308**	0.292	0.325
9	+	7	8	12	10	14	1	2	3	1.0000	0.0325*	1.0000	0.517	0.282	0.753
	−	9	4	12	4	5	16	13	43	0.0466*	0.3052	0.1056	0.330**	0.434	0.227**
	+−	16	12	24	14	19	17	15	46	0.0018**	0.0603	0.0247*	0.287**	0.324	0.250**
L	+	4	5	4	8	5	3	2	3	1.0000	0.3052	1.0000	0.654	0.516	0.792
	−	7	5	19	6	7	24	14	52	0.0078**	0.1250	0.0325*	0.262**	0.351	0.172**
	+−	11	10	23	14	12	27	16	55	0.0078**	0.1250	0.0603	0.317**	0.382	0.251**

Table 5
Autocorrelation of daily *individual* stock returns: open-to-close returns (Null Hypothesis IV). We report the number of firms exhibiting positive (+), negative (−), and two-sided (+−) significant autocorrelation at the 2.5% one-sided (5% two-sided) levels. We report a *p*-value, p_3, derived from the first and second order statistics (minimum and second lowest) of the observations for the eight two-year time-horizon subperiods in 93–08, as well as for the four two-year time-horizon subperiods in 93–00 and 01–08. We also report p_4, the average of the *p*-values over the eight or four two-year time-horizon subperiods; p_4 is not itself a *p*-value, and significance levels are determined by Monte Carlo simulation. ***, **, and * denote significance at the 0.1%, 1%, and 5% levels. Pearson correlation tests are used in this table; results using the Andrews test and Kendall τ-test are reported in Panels B and C of Table A2 of Anderson et al. (2012).

Portfolio		Autocorrelation of daily *individual* stock returns: open-to-close returns								Binomial *p*-value			Average *p*-value		
		93–94	95–96	97–98	99–00	01–02	03–04	05–06	07–08	93–08	93–00	01–08	93–08	93–00	01–08
										p_3	p_3	p_3	p_4	p_4	p_4
Pearson correlation test															
Smallest	+	8	17	34	19	24	18	8	11	0.0002***	0.0191*	0.0191*	0.181***	0.166**	0.196**
	−	6	6	5	13	12	14	14	48	0.0078**	0.1250	0.0038**	0.268**	0.381	0.154**
	+−	14	23	39	32	36	32	22	59	0.0004***	0.0325*	0.0053**	0.183***	0.215**	0.152**
2	+	22	19	44	23	14	7	5	7	0.0078**	0.0006***	0.1250	0.225**	0.103**	0.348
	−	5	5	2	8	16	24	16	34	0.0703	1.0000	0.0012**	0.350	0.578	0.123**
	+−	27	24	46	31	30	31	21	41	0.0000***	0.0038**	0.0064**	0.169***	0.166**	0.172**
3	+	21	22	39	24	10	0	4	7	0.2701	0.0004***	1.0000	0.329**	0.100**	0.558
	−	5	5	3	4	29	24	11	42	0.2701	0.9645	0.0053**	0.367	0.615	0.119**
	+−	26	27	42	28	39	24	15	49	0.0002***	0.0027**	0.0247*	0.181***	0.169**	0.193**
4	+	33	22	36	18	6	0	5	8	0.0703	0.0007***	1.0000	0.328**	0.099**	0.557
	−	3	4	3	14	29	29	17	38	0.4651	0.9645	0.0009***	0.357	0.618	0.096***
	+−	36	26	39	32	35	29	22	46	0.0000***	0.0027**	0.0053**	0.158***	0.154**	0.163**
5	+	31	27	22	11	4	7	6	10	0.0222*	0.0053**	0.3052	0.270**	0.129**	0.412
	−	7	6	11	8	18	28	4	24	0.0222*	0.0603	0.0406*	0.284**	0.328	0.239**
	+−	38	33	33	19	22	35	10	34	0.0011**	0.0096**	0.1250	0.214**	0.174**	0.254**
6	+	25	15	12	6	6	9	3	5	0.0703	0.0603	0.9645	0.365	0.223**	0.507
	−	0	7	12	14	13	15	4	24	0.2701	0.6312	0.1056	0.354	0.436	0.272
	+−	25	22	24	20	19	24	7	29	0.0011**	0.0078**	0.2628	0.280**	0.221**	0.340
7	+	29	19	16	8	4	6	2	6	0.2701	0.0191*	1.0000	0.393	0.172**	0.615
	−	5	12	11	9	13	7	11	28	0.0078**	0.1250	0.0325*	0.260**	0.303	0.217**
	+−	34	31	27	17	17	13	13	34	0.0010***	0.0150*	0.0438*	0.250**	0.197**	0.303
8	+	25	10	4	8	5	4	5	6	0.0466*	0.3052	0.3052	0.416	0.322	0.510
	−	2	5	15	9	6	10	3	25	1.0000	1.0000	0.9645	0.443	0.486	0.400
	+−	27	15	19	17	11	14	8	31	0.0386*	0.0247*	0.3052	0.334	0.269	0.399
9	+	10	11	12	7	16	2	3	6	1.0000	0.0325*	1.0000	0.431	0.261**	0.602
	−	4	8	14	3	5	10	11	34	0.2701	0.9645	0.1250	0.375	0.487	0.263
	+−	14	19	26	10	21	12	14	40	0.0078**	0.1250	0.0603	0.306**	0.328	0.284
Largest	+	9	3	4	6	7	0	5	0	1.0000	0.9645	1.0000	0.626	0.538	0.714
	−	5	8	31	7	7	17	8	40	0.0078**	0.1250	0.0325*	0.266**	0.313	0.220**
	+−	14	11	35	13	14	17	13	40	0.0036**	0.0854	0.0438*	0.313**	0.335	0.290

Null Hypothesis III is rejected at the 0.1% level among nine of ten firm-size groups for the whole data period, and at the 5% level or better among nine of ten firm-size groups for both the first and second halves of our data period.[9] The significant autocorrelations are predominantly positive in the first half; all but one of the significant autocorrelations in the second half are negative. Both positive and negative autocorrelations can only come from PPA.

Our *Null Hypothesis IV* is that the autocorrelation of open-to-close returns on *each* stock is zero in each two-year subperiod. The testing procedure and rejection criteria are identical to those for Null Hypothesis II. Rejection of Null Hypothesis IV, whether positive or negative, implies that PPA is a source of individual stock return autocorrelation. Table 5 reports our main results on individual open-to-close stock returns. Null Hypothesis IV is rejected at the 5% level or better for all ten of our firm size groups for the Pearson test. Very similar results are obtained by comparing p_4, the average of the *p*-values to a distribution obtained by Monte Carlo simulation. The significant autocorrelations in the first half of our data period are overwhelmingly positive, while those in the second half are overwhelmingly negative. All reflect PPA.

2.4.3. Analysis of autocovariance

The three key ideas outlined above allow us to identify certain elements of autocorrelation that can only come from PPA. For each stock, we can compute the conventional daily (open-to-close) return autocovariance by taking the product of the conventional daily (open-to-close) return autocorrelation times the conventional daily (open-to-close) return variance. Note that these autocovariances can be either positive or negative, so it is not appropriate to compute their ratio. However, we know that PPA is the only source of the open-to-close return autocovariance. If C_i and I_i denote the conventional daily and open-to-close

[9] For brevity, we do not provide the table here. See Table 6 of Anderson et al. (2012).

return autocovariances of stock i; $C_i - I_i$ denotes the residual. C_i, I_i, and $C_i - I_i$ may each be either positive or negative. Thus, we consider $\frac{|I_i|}{|I_i|+|C_i-I_i|}$ as the fraction of the identifiable absolute autocovariance arising from open-to-close returns. This ratio is a lower bound on the portion of the identifiable return autocorrelation attributable to PPA. It understates the proportion of the autocorrelation attributable to PPA for two reasons. First, PPA can induce both negative and positive effects; these cancel, and we see only the net effect in this calculation. Second, PPA occurring between the last trade of a stock on a given day and the first trade on the next day is also omitted from this calculation.

Averaging over the ten firm-size groups within each two-year time-horizon subperiod, our estimates are that at least 55.8% of average individual stock covariance among our 1000 stocks came from PPA in 1993–94, 53.3% in 1995–96, 61.2% in 1997–98, 57.3% in 1999–2000, 58.1% in 2001–02, 56.5% in 2003–04, 53.3% in 2005–06, and 57.6% in 2007–08. Averaging over the eight two-year time-horizon subperiods within each firm-size group, we estimate that at least 56.7% of individual stock covariance in the group of smallest firms came from PPA over our sixteen-year data period, 59.8% in group 2, 60.0% in group 3, 60.7% in group 4, 59.4% in group 5, 55.7% in group 6, 54.5% in group 7, 53.5% in group 8, 53.8% in group 9, and 52.3% in the group of largest firms. The average over firm size groups is remarkably stable across time periods, as is the average over time periods across firm size groups.

2.4.4. Summary: individual stock return autocorrelation

The following are our main findings for *individual* stock return autocorrelation:

- We reject the hypothesis that the average individual conventional stock return autocorrelation is zero, and the hypothesis that the conventional return autocorrelation for each stock is zero. Given the differences in liquidity and other market characteristics between large and small stocks, the uniformity of the results across firm size groups is surprising. The autocorrelations are predominantly positive in the first half of our data period (1993–2000), and predominantly negative in the second half (2001–2008). The positive autocorrelations can only come from PPA, while the negative autocorrelations may come from any combination of NT, BAB, and PPA.
- We also reject the hypothesis that the average individual open-to-close stock return autocorrelation is zero, and the hypothesis that the open-to-close return autocorrelation for each stock is zero. Even though this approach excludes NT and BAB, the results are qualitatively similar to those obtained with conventional returns. The autocorrelations are predominantly positive in the first half of our data period, and predominantly negative in the second half. Both the positive and negative autocorrelations can only arise from PPA.
- As a robustness check, all tests using the Pearson test were rerun using the Andrews and Kendall tests, with qualitatively similar results.[10]

2.5. Portfolio returns

We study portfolio return autocorrelation first by taking each of our size groups as an equally-weighted portfolio, using both conventional and open-to-close returns on the individual stocks in the portfolio. Second, we consider the conventional daily return autocorrelation of SPDRs. Finally, we analyze the correlation between past returns on the SPDRs and future returns on the individual stocks in each of the size groups by counting the number of stocks with statistically significant autocorrelation in each size group and each two-year return subperiod.

While many papers have studied whether NT can fully explain positive portfolio autocorrelation, all of the tests have been indirect; see Atchison et al. (1987), Lo and MacKinlay (1990), Boudoukh et al. (1994), Ahn et al. (2002), and Bernhardt and Davies (2008). In this paper, we propose and carry out two direct tests that eliminate NT. In both tests, we compute the correlation of securities returns over disjoint time intervals separated by a trade, so that stale prices never enter the correlation calculation. If NT and BAB are the sole explanations of portfolio return autocorrelation, the autocorrelation computed by our methods must be less than or equal to zero.

As a preliminary test, we consider conventional portfolio returns as a benchmark. The conventional daily return of a portfolio is defined to be an equally weighted average of the conventional daily returns of the individual stocks in the portfolio. *Null Hypothesis V* is that the conventional daily return autocorrelation is zero in each of the ten portfolios and each of the eight two-year time-horizon subperiods. The binomial analysis presented in Table 6 rejects the Null Hypothesis V at the 1% level or better, for all ten portfolios and all eight subperiods over the sixteen-year data period 1993–2008.[11] In the first half of our data period, the null hypothesis is rejected at the 0.1% level for all but the largest firm-size portfolio. By contrast, in the second half of our data period, the null hypothesis is not rejected for any portfolio. The portfolio autocorrelations in the single two-year subperiod 2007–08 are negative for all but one firm-size portfolio, with a mixture of significant and insignificant results. Since NT should be positive, this suggests that PPA was significant and negative in 2007–08, presumably as a result of the extreme volatility of that period. Apart from 2007–08, all but one of the significant autocorrelations in the other two-year subperiods are positive. As the firm size becomes larger, the first-order autocorrelation of portfolio return becomes smaller; this is consistent with the previous studies (e.g., Chordia and Swaminathan (2000, Table I on page 917)).

[10] The results using the Andrews and Kendall tests may be found in Anderson et al. (2012).

[11] Results using the Andrews and Kendall tests are presented in Panels B and C of Table 8 of Anderson et al. (2012).

Table 6
First-order autocorrelation of daily *portfolio* returns: conventional daily returns (Null Hypothesis V). Numbers in parenthesis are standard errors, computed for the Pearson tests. The final three columns report *p*-values from the binomial tests based on counting the number of two-year subperiods in which the autocorrelation of a given firm-size portfolio conventional daily return is statistically significant at the 5% level. ***, **, and * denote significance at the 0.1%, 1%, and 5% levels, respectively. Results for the Andrews and Kendall tests are reported in Panels B and C of Table 8 of Anderson et al. (2012).

Portfolio	First-order autocorrelation of *portfolio* returns: conventional daily returns											Binomial *p*-value		
	93–94	95–96	97–98	99–00	01–02	03–04	05–06	07–08	93–08	93–00	01–08	93–08	93–00	00–08
Pearson correlation test														
Smallest	0.221^{**}	0.136^{**}	0.300^{**}	0.231^{**}	0.144^{**}	0.051	0.059	-0.102^{*}	0.008	0.233^{**}	−0.034	0.0000^{***}	0.0000^{***}	0.0140^{*}
2	0.240^{**}	0.142^{**}	0.286^{**}	0.211^{**}	−0.003	0.026	0.009	-0.089^{*}	−0.006	0.232^{**}	-0.049^{*}	0.0000^{***}	0.0000^{***}	0.1855
3	0.210^{**}	0.212^{**}	0.276^{**}	0.157^{**}	−0.035	0.001	0.019	−0.059	0.009	0.216^{**}	−0.037	0.0004^{***}	0.0000^{***}	1.0000
4	0.258^{**}	0.174^{**}	0.287^{**}	0.092^{*}	−0.052	−0.027	0.006	−0.023	0.016	0.201^{**}	−0.025	0.0004^{***}	0.0000^{***}	1.0000
5	0.264^{**}	0.192^{**}	0.211^{**}	0.151^{**}	0.028	0.044	0.073	0.006	0.060^{**}	0.194^{**}	0.023	0.0004^{***}	0.0000^{***}	1.0000
6	0.258^{**}	0.192^{**}	0.201^{**}	0.085	0.046	0.025	0.083	−0.022	0.048^{**}	0.162^{**}	0.009	0.0058^{**}	0.0005^{***}	1.0000
7	0.220^{**}	0.170^{**}	0.208^{**}	0.080	0.097^{*}	0.032	0.058	−0.016	0.053^{**}	0.158^{**}	0.020	0.0004^{***}	0.0005^{***}	0.1855
8	0.217^{**}	0.158^{**}	0.141^{**}	0.111^{*}	0.058	0.006	0.024	−0.028	0.035^{*}	0.144^{**}	−0.001	0.0004^{***}	0.0000^{***}	1.0000
9	0.139^{**}	0.146^{**}	0.054	0.112^{*}	0.085	−0.041	−0.003	−0.073	0.007	0.098^{**}	−0.026	0.0058^{**}	0.0005^{***}	1.0000
Largest	0.025	0.115^{**}	−0.003	0.083	0.028	−0.068	−0.054	−0.082	−0.017	0.048^{*}	-0.047^{*}	0.0036^{**}	0.1855	1.0000
	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.016)	(0.022)	(0.022)			

Table 7
First-order autocorrelation of daily *portfolio* returns: open-to-close returns (Null Hypothesis VI). Numbers in parenthesis are standard errors. The final three columns report p-values from the binomial tests based on counting the number of two-year subperiods in which the autocorrelation of a given firm-size portfolio daily open-to-close return is statistically significant at the 5% level. ***, **, and * denote significance at the 0.1%, 1% and 5% levels, respectively. Pearson correlation tests are used in this table; results using the Andrews and Kendall tests are reported in Panels B and C of Table 9 of Anderson et al. (2012).

Portfolio	First-order autocorrelation of daily portfolio returns: open-to-close returns											Binomial p-value		
	93–94	95–96	97–98	99–00	01–02	03–04	05–06	07–08	93–08	93–00	01–08	93–08	93–00	00–08
Pearson correlation test														
Smallest	0.165**	0.126**	0.249**	0.215**	0.124**	0.043	0.054	−0.120**	−0.010	0.211**	−0.048*	0.0000***	0.0000***	0.0140*
2	0.211**	0.164**	0.261**	0.215**	−0.013	0.026	0.004	−0.098*	−0.015	0.232**	−0.055*	0.0000***	0.0000***	0.1855
3	0.171**	0.232**	0.249**	0.180**	−0.050	−0.001	0.010	−0.087	−0.008	0.214**	−0.056*	0.0004***	0.0000***	1.0000
4	0.229**	0.212**	0.300**	0.107*	−0.061	−0.018	0.009	−0.045	0.007	0.211**	−0.038	0.0004***	0.0000***	1.0000
5	0.218**	0.208**	0.203**	0.180**	0.018	0.030	0.055	−0.010	0.050**	0.196**	0.008	0.0004***	0.0000***	0.1855
6	0.225**	0.209**	0.165**	0.124**	0.022	0.025	0.084	−0.027	0.043**	0.161**	0.001	0.0004***	0.0000***	0.1855
7	0.195**	0.156**	0.181**	0.132**	0.064	0.034	0.069	−0.048	0.034*	0.160**	−0.006	0.0004***	0.0000***	0.1855
8	0.187**	0.122**	0.062	0.165**	0.054	0.010	0.062	−0.045	0.023	0.123**	−0.009	0.0058**	0.0005**	1.0000
9	0.079	0.053	−0.034	0.136**	0.063	−0.031	0.030	−0.086	−0.008	0.055*	−0.033	0.3366	0.1855	1.0000
Largest	−0.041	−0.029	−0.101	0.068	0.000	−0.075	−0.024	−0.109*	−0.052**	−0.017	−0.069**	0.0058**	0.1855	0.1855
	(0.045)	(0.044)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.016)	(0.022)	(0.022)			

Table 8
Lower bound on proportion of PPA in the autocorrelation of the portfolio returns. The lower bound on the proportion of PPA in the autocorrelation of the portfolio returns is computed as follows:

$$\frac{|I_i|}{|I_i| + |C_i - I_i|}$$

where C_i and I_i denote the conventional daily and open-to-close return autocovariances of stock i; $C_i - I_i$ denotes the residual. C_i, I_i, and $C_i - I_i$ may each be either positive or negative.

Portfolio	Open-to-close return autocovariance as percentage of open-to-close plus residual return autocovariance									
	93–94	95–96	97–98	99–00	01–02	03–04	05–06	07–08	Avg. 93–08	Avg. 93–00	Avg. 01–08
Smallest	0.5888	0.6472	0.6276	0.7577	0.7163	0.7053	0.7962	0.9930	0.7290	0.6553	0.8027
2	0.6487	0.8534	0.7175	0.8609	0.5753	0.8718	0.4172	0.9121	0.7321	0.7701	0.6941
3	0.6245	0.7853	0.7367	0.9724	0.8592	0.3576	0.4461	0.8496	0.7039	0.7797	0.6281
4	0.6989	0.8749	0.7954	0.9732	0.9597	0.5797	0.8033	0.7283	0.8017	0.8356	0.7678
5	0.6385	0.7594	0.7311	0.9933	0.5311	0.5780	0.6423	0.3631	0.6546	0.7806	0.5286
6	0.6498	0.7784	0.6271	0.8556	0.3714	0.8554	0.8450	0.9408	0.7404	0.7277	0.7531
7	0.6758	0.6568	0.6744	0.8023	0.5065	0.8649	0.9769	0.6380	0.7245	0.7023	0.7466
8	0.6702	0.5600	0.3394	0.9051	0.7008	0.7938	0.6523	0.8380	0.6824	0.6187	0.7462
9	0.4311	0.2649	0.2472	0.9131	0.5677	0.6203	0.4716	0.8212	0.5421	0.4641	0.6202
Largest	0.3565	0.1428	0.5097	0.5933	0.0051	0.9258	0.3588	0.9402	0.4790	0.4006	0.5574
Average	0.5983	0.6323	0.6006	0.8627	0.5793	0.7153	0.6410	0.8024			

2.5.1. First method, open-to-close returns

In the first method, we compute the open-to-close returns of each individual stock. As noted in Section 2.1.2, open-to-close returns on different days do not exhibit NT, and BAB should be essentially eliminated. In each two-year time-horizon subperiod, we consider each of the ten groups of 100 stocks, grouped by market capitalization, that were used in our individual stock return studies: we form a portfolio from each group.

We define the open-to-close return of a portfolio on a given day as the equally-weighted average of the open-to-close returns for that day on all stocks in the portfolio, omitting those stocks which have fewer than two trades on that day. Note that the autocorrelation of the open-to-close return of the portfolio is just the average of the correlations of the open-to-close returns of the individual pairs (including the diagonal pairs) of stocks in the portfolio. Since 99% of these pairs are off-diagonal, the portfolio return autocorrelation is dominated by the cross-autocorrelations between pairs of stocks. In particular, the portfolio return autocorrelation is *not* the average of the individual return own autocorrelations of the stocks in the portfolio.

If PPA makes no contribution to portfolio return autocorrelation, the theoretical autocorrelation of the open-to-close return of the portfolio must be zero. Thus, our *Null Hypothesis VI* is that the autocorrelation of the open-to-close return of the portfolio is zero in each of the eight two-year subperiods. Table 7 presents the results of our tests of Null Hypothesis VI. Over the whole data period, the binomial analysis indicates that Null Hypothesis VI is rejected at the 1% or better level in eight of the ten portfolios, the two exceptions being the two largest size portfolios. We find strong autocorrelations in the first half of our data period, but much weaker autocorrelation in the second half. For individual portfolios and two-year time-horizon subperiods, all the significant autocorrelations are positive, except for 2007–08, where all of the autocorrelations (whether significant or not) are negative. Interestingly, the point estimates for the largest firm-size portfolio are mostly negative, and they are significant and negative over the entire sixteen-year subperiod, but not in the binomial tests based on the eight two-year subperiods. Thus, our results provide strong evidence of PPA in the eight smaller-firm-size portfolios, and some evidence of PPA in the largest-firm-size portfolio.

Table 8 provides a lower bound of the identifiable absolute autocovariance of individual stocks arising from PPA in each firm-size group of stocks and each of the eight two-year time-horizon subperiods. Averaging over the ten firm-size groups within each two-year subperiod, the lower bound on the portion of the autocorrelation attributable to PPA ranges from 57.9% (in 2001–02) to 80.2% (in 2007–08) and 86.27% (in 1999–2000). 1999–2000 was a period of rapid growth, peaking in early 2000, followed by a sharp decline; however, 2007–08 saw a sharp decline but no turnaround (the market low occurred in March 2009). This suggests to us that the high level of PPA is more related to market volatility than a regression to the max issue. Averaging over the eight two-year subperiods within each firm-size group, the lower bound ranges from 47.9% (in the group of largest firms) to 80.2% (in the fourth group by firm size).

2.5.2. Second method, ETFs

In the second method, we take our portfolio to be an ETF. ETFs are continuously-traded securities which represent ownership of the stocks in a particular mutual fund or index. Because a mutual fund is valued once a day, and an index is calculated at any given instant by averaging the most recent price of each stock in the index, and some of those prices are stale, the mutual funds and indices are themselves subject to NT.

For example, the quoted value of the S&P 500 index exhibits stale pricing because it is an average of the most recent trade price of the stocks in the index. ETFs are traded continuously and very actively, and the value is updated continuously, rather than with lags arising from intervals between trades of the underlying stocks. At any instant, each stock price is somewhat stale because it has not been adjusted since the last trade, so the index exhibits staleness; however, each trade of the ETF represents an actual trade, which by definition is not stale at the time it occurs. In particular, each trade of the ETF occurs at a price different from the

Table 9
SPDR autocorrelation. Exchange: A denotes AMEX, N Nasdaq; we use the exchange with the highest SPDR volume during the regular trading session; this was initially AMEX, but shifted to Nasdaq during 2001–02. RMSSR is the root mean square spread ratio. The effect of BAB on the Pearson correlation coefficient cannot exceed $(\mathrm{RMSSR}/\sigma)^2$, and should generally be much lower. For example, in the Roll (1984) model, the effect of BAB on the Pearson correlation coefficient is the $(\mathrm{RMSSR}/\sigma)^2$, divided by four. *** and ** denote significance at the 0.1% and 1% levels.

Year	Exchange	No. of obs.	Pearson acf	*t*-value	Std. dev. σ (%)	RMSSR (%)	$(\mathrm{RMSSR}/\sigma)^2$	Pearson corrected for BAB by $(\mathrm{RMSSR}/\sigma)^2$ (upper bound on BAB)	*t*-value	Pearson corrected for BAB by $(\mathrm{RMSSR}/\sigma)^2/4$ (Roll's model)	*t*-value
1993–94	A	486	−0.039	−0.86	0.6291	0.0682	0.01175	−0.027	−0.60	−0.036	−0.76
1995–96	A	506	0.026	0.58	0.6794	0.1013	0.02223	0.048	1.08	0.032	0.71
1997–98	A	505	−0.074	−1.66	1.2669	0.1556	0.01509	−0.059	−1.32	−0.070	−1.58
1999–00	A	504	−0.014	−0.31	1.2973	0.1330	0.01051	−0.003	−0.08	−0.011	−0.25
2001–02	A&N	500	−0.017	−0.38	1.5264	0.0962	0.00397	−0.013	−0.29	−0.016	−0.36
2003–04	N	504	−0.086	−1.93	0.9062	0.1443	0.02536	−0.061	−1.36	−0.080	−1.79
2005–06	N	503	−0.046	−1.03	0.6387	0.0555	0.00755	−0.038	−0.86	−0.044	−0.99
2007–08	N	504	−0.146	−3.30***	1.9036	0.0199	0.00011	−0.146	−3.30***	−0.146	−3.30***
1993–2008		4012	−0.067	−4.25***	1.1922	0.1083	0.00825	−0.059	−3.73***	−0.065	−4.12**
1993–2000		2001	−0.033	−1.48	1.0210	0.1195	0.01370	−0.019	−0.86	−0.030	−1.32
2001–2008		2011	−0.089	−4.00***	1.3403	0.0940	0.00492	−0.084	−3.78***	−0.088	−3.95***

Table 10
ETFs (Null Hypothesis VII). We report the number of firms exhibiting positive (+), negative (−), and two-sided (+−) significant correlation with the prior SPDR return at the 2.5% one-sided (5% two-sided) levels. We report a *p*-value, p_3, derived from the first and second order statistics (minimum and second lowest) of the observations for the eight two-year time-horizon subperiods in 93–08, as well as for the four two-year time-horizon subperiods in 93–00 and 01–08. We also report p_4, the average of the *p*-values over the eight or four two-year time-horizon subperiods; p_4 is not itself a *p*-value, and significance levels are determined by Monte Carlo simulation. ***, **, and * denote significance at the 0.1%, 1%, and 5% levels. Pearson correlation tests are used in this table; results using the Andrews test and Kendall τ-test are reported in Table A3 of Anderson et al. (2012).

Portfolio		Correlation of daily *individual* stock returns and SPDRs								Binomial *p*-value			Average *p*-value		
		93–94	95–96	97–98	99–00	01–02	03–04	05–06	07–08	93–08	93–00	01–08	93–08	93–00	01–08
		Pearson correlation test								p_3	p_3	p_3	p_4	p_4	p_4
Smallest	+	14	18	30	11	15	10	20	5	0.0008***	0.0053**	0.1250	0.209**	0.157**	0.260**
	−	0	1	1	0	3	8	7	41	1.0000	1.0000	0.6312	0.695	1.000	0.391
	+−	14	19	31	11	18	18	27	46	0.0036**	0.0854	0.0119*	0.261**	0.309	0.212**
2	+	22	21	33	13	7	3	4	6	0.2701	0.0027**	0.9645	0.342	0.125**	0.558
	−	0	2	1	0	14	9	7	37	1.0000	1.0000	0.0325*	0.610	1.000	0.220**
	+−	22	23	34	13	21	12	11	43	0.0036**	0.0438*	0.0854	0.275**	0.244**	0.306
3	+	30	33	30	18	6	6	8	7	0.0018**	0.0007***	0.0603	0.236**	0.095***	0.376
	−	2	0	5	2	18	11	8	45	1.0000	1.0000	0.0191*	0.529	0.875	0.184**
	+−	32	33	35	20	24	17	16	52	0.0002***	0.0078**	0.0191*	0.201**	0.175**	0.228**
4	+	29	31	34	16	6	4	6	8	0.0222*	0.0012**	0.3052	0.271**	0.099**	0.443
	−	0	0	2	7	15	11	12	36	1.0000	1.0000	0.0053**	0.504	0.839	0.168**
	+−	29	31	36	23	21	15	18	44	0.0003***	0.0045**	0.0247*	0.207**	0.172**	0.241**
5	+	35	29	29	18	11	8	17	10	0.0002***	0.0007***	0.0191*	0.165***	0.096***	0.234**
	−	0	0	9	6	14	10	2	28	1.0000	1.0000	0.2266	0.527	0.674	0.379
	+−	35	29	38	24	25	18	19	38	0.0001***	0.0038**	0.0119*	0.191***	0.164**	0.218**
6	+	41	27	29	12	10	8	15	11	0.0002***	0.0038**	0.0191*	0.176***	0.112**	0.239**
	−	0	1	6	11	6	6	2	17	1.0000	1.0000	0.9766	0.578	0.661	0.495
	+−	41	28	35	23	16	14	17	28	0.0005***	0.0045**	0.0325*	0.225**	0.165**	0.286
7	+	37	35	36	15	20	5	14	14	0.0001***	0.0015**	0.0850	0.170***	0.094***	0.246**
	−	0	0	3	13	1	2	3	21	1.0000	1.0000	1.0000	0.747	0.756	0.738
	+−	37	35	39	28	21	7	17	35	0.0023**	0.0020**	0.3622	0.247**	0.146**	0.347
8	+	28	31	26	9	19	4	5	11	0.0466*	0.0119*	0.3052	0.253**	0.136**	0.371
	−	0	0	9	15	1	4	3	30	1.0000	1.0000	1.0000	0.623	0.611	0.635
	+−	28	31	35	24	20	8	8	41	0.0466*	0.0038**	0.3052	0.289**	0.173**	0.405
9	+	25	32	14	16	14	1	3	5	1.0000	0.0020**	1.0000	0.378	0.128**	0.628
	−	3	0	12	22	4	15	8	34	1.0000	1.0000	0.3052	0.417	0.539	0.294
	+−	28	32	26	38	18	16	11	39	0.0034**	0.0027**	0.0854	0.229**	0.165**	0.293
Largest	+	12	27	8	10	5	0	1	7	1.0000	0.0191*	1.0000	0.465	0.216**	0.714
	−	4	0	16	16	4	28	10	47	0.2701	1.0000	0.2266	0.369	0.484	0.254**
	+−	16	27	24	26	9	28	11	54	0.0181*	0.0191*	0.1905	0.272**	0.225**	0.320

current value of the index; in the absence of PPA, the ETF price should reflect all the information in the market, including the "correct" price of the stocks in the index, even if many of those stocks have not traded for some time.

For this paper, the ETF we choose is SPDRs, an ETF based on the S&P 500 index; each SPDR share represents a claim to one-tenth of the value of the S&P 500 index. Since SPDRs are a single security, NT arises only from days on which no trade occurs; since SPDRs are traded extremely actively, NT makes no contribution to the SPDRs' return autocorrelation. SPDRs are subject to TVRP, but TVRP results in positive autocorrelation, and our SPDR autocorrelations are negative in seven of the eight two-year subperiods. As a single security priced on a grid, SPDRs exhibit BAB.

Before proceeding to the main test, we test whether SPDR autocorrelation can be explained by BAB. In the Roll (1984) model of BAB, the choice of the bid or ask price at each successive trade is given by an IID toss of a fair coin. In that model, assuming the absence of PPA, the autocovariance of percentage returns arising from BAB is equal to minus the mean square spread ratio (MSSR) divided by 4.[12] In practice, it seems likely that the successive coin tosses are positively serially correlated, in which case the autocovariance induced by BAB is smaller in magnitude than MSSR/4. It is only if the successive coin tosses are *negatively* serially correlated that the autocovariance induced by BAB exceeds MSSR/4 in magnitude, but it can never exceed MSSR; that upper bound is achieved only in the extreme case in which the successive coin tosses are deterministic and strictly alternate between heads and tails.

Table 9 presents the results of our test for autocorrelation of conventional daily SPDR returns, with corrections to eliminate any autocorrelation arising from BAB. In seven of the eight two-year time-horizon subperiods, the SPDRs exhibit negative autocorrelation, but the autocorrelation is statistically significant only in the 2007–08 subperiod. The autocorrelation is negative and statistically significant at the 0.1% level for 2007–08, for the second half of our data period 2001–08, and for the entire data period 1993–2008. We correct for the maximum possible contribution of BAB, by adding $MSSR/\sigma^2 = (RMSSR/\sigma)^2$ to the Pearson correlation coefficient; this makes little difference in the Pearson correlation coefficient, and the results remain significant at the 0.1% level. This indicates that PPA, in the form of overshooting, is the main source of negative autocorrelation in the SPDR returns.

[12] See Roll (1984), in particular Eq. (1) on page 1129, footnote 5 on page 1130, and the sentence preceding that footnote.

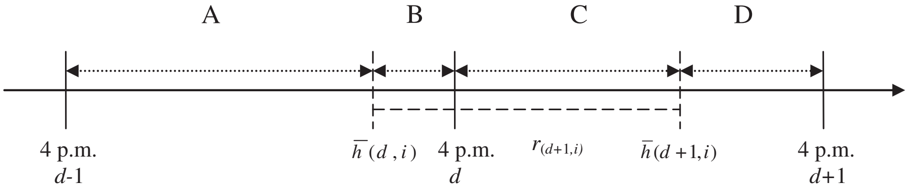

Fig. 1. Time diagram for Null Hypothesis VII. Our Null Hypothesis VII is that the correlation of each of the individual stock returns and the return of the SPDRs is zero. $r_{(d+1,i)}$ is the daily return of each individual stock on day $d+1$, computed in the conventional way. We compute the correlation between the return of stock i on day $d+1$ (in other words, the return from the final trade of the stock on day d to the final trade of the stock on day $d+1$, corresponding to the intervals B and C) with the return of the SPDRs over the interval from the time of the last trade of the SPDRs on day $d-1$ through the time of the last trade of the *stock* on day d, corresponding to the interval A.

Our main test using ETFs is whether the past returns of SPDRs are correlated with the future returns of individual stocks. The daily return of each individual stock is computed in the conventional way. We compute the correlation between the conventional return of stock i on day $d+1$ (in other words, the return over the period from the final trade of the stock on day d to the final trade of the stock on day $d+1$) with the return of the SPDRs over the period from the time of the last trade of the SPDRs on day $d-1$ through the time of the last trade of the *stock* on day d. If a stock does not trade on day d or the stock does not trade on day $d+1$, we omit the data from our calculation.

Note that each time we compute a correlation, it is the correlation of a stock return over a given return period with the return of a traded security, SPDRs, over a disjoint return period, with both the SPDRs and the stock trading in the interval separating the two return periods. Thus, the calculation of the correlation does not use stale prices, and hence there is no NT effect. Since BAB turns out not to be a significant source of return autocorrelation for the SPDRs at the level of two-year time-horizon subperiods (see Table 9), since the stock is a different security from the SPDRs, and since the stock trades occur at different times from the SPDR trades, any BAB between the SPDRs and the individual stock will be virtually eliminated and can be ignored.

Thus, in the absence of PPA, the correlation between the return of the individual stock and the return of the SPDR, computed over disjoint time intervals, must be zero. Our Null Hypothesis VII is that the correlation of each of the individual stock returns and the return of the SPDRs is zero in each of the eight two-year time-horizon subperiods. As noted in Table 10, Null Hypothesis VII is rejected at the 5% or better level for all ten firm-size portfolios using the both the binomial and average p-value tests, with correlations calculated using the Pearson test. For both the binomial and average p-value tests, the vast majority of the rejections are at the 1% level, and many are at the 0.1% level, with somewhat higher significance levels for the average p-value tests.

The significant autocorrelations in portfolios within two-year time-horizon subperiods are disproportionately positive in the first half of our data period and disproportionately negative in the second half. All are evidence of PPA.

Because the definitions underlying Null Hypothesis VII are somewhat complex, we here present a more formal statement of the model. Assuming closing time is 4:00 p.m., we define the following notation:

$S_{(d,h)i}$	Price of stock i at hour h on date d,
$\bar{S}_{(d,h)}$	Price of SPDRs at hour h on date d,
$h(d,i)$	Hour of last trade of stock i on date d,
$\bar{h}(d,i)$	$\min\{h(d,i), 4{:}00\ p.m.\}$,
S_{di}	$S_{(d,h(d,i))i}$ (the closing price),

$$\bar{S}_d = \bar{S}_{d,4p.m.},$$

$$r_{di} = \frac{S_{di}\text{-}S_{(d-1)i}}{S_{(d-1)i}},$$

$$\bar{r}_d = \frac{\bar{S}_d - \bar{S}_{d-1}}{\bar{S}_{d-1}},$$

where "hour" means the date-stamp time of the transaction, to the hundredth of a second; as noted above, we do make use of some transactions time-stamped after the close of trade at 4:00 p.m., representing the execution of market-on-close orders.

We decompose the daily return of the SPDRs, $\frac{\bar{S}_d - \bar{S}_{d-1}}{\bar{S}_{d-1}}$, into two components, $\frac{\bar{S}_d - \bar{S}_{d,\bar{h}(d,i))}}{\bar{S}_{d-1}}$ and $\frac{\bar{S}_{d,\bar{h}(d,i)} - \bar{S}_{d-1}}{\bar{S}_{d-1}}$. No stale prices are used in the calculation of $Corr\left(r_{(d+1)i}, \frac{\bar{S}_{d,\bar{h}(d,i)} - \bar{S}_{d-1}}{\bar{S}_{d-1}}\right)$, the correlation between the return of stock i tomorrow and today's return of SPDRs up to the time of the stock i's today's last transaction; note that if the last stock trade is time-stamped 4:10 p.m., representing the execution of a market-on-close order placed before 4:00 p.m., we use the last SPDR trade time-stamped before 4:00 p.m., to ensure there is no overlap in the time intervals. These two returns are computed on disjoint return periods separated by trades, as we can see in Fig. 1, so there is no NT effect. For the reasons given above, BAB can be ignored. In the absence of PPA, the correlation must be zero.

$$Corr\left(r_{(d+1)i}, \frac{\overline{S}_{d,\overline{h}(d,i)} - \overline{S}_{d-1}}{\overline{S}_{d-1}}\right) = 0. \tag{1}$$

Our test detects only that portion of PPA arising from the slow incorporation of the very public, non-firm-specific, information contained in the price of SPDRs into the price of individual firms. The remainder, which presumably constitutes the vast majority of the total PPA present in the market, is not captured by this test.

As a robustness check, to test whether the lags in incorporating information into SPDR returns documented by Hasbrouck (1996, 2003) can explain our findings, we reran our tests for the three largest firm size groups, calculating the SPDR return over a return period ending three minutes before the last trade of the stock. The results, reported in Table 13 of Anderson et al. (2012), change very little, indicating that the lags documented by Hasbrouck cannot explain our findings.

Our evidence for PPA in large firms is considerably stronger in the SPDR tests than in the portfolio open-to-close return tests. The time interval between a stock trade and the last previous SPDR trade is, in the latter part of our data period, a small fraction of a second; in our tests with lagged SPDR data, the time interval is three minutes. By contrast, in the portfolio open-to-close return tests, the time interval between the first trade on day $d + 1$ and the last trade on day d includes an entire overnight period, and it appears that large stock prices do adjust fairly completely to information overnight, reducing but not entirely eliminating the autocorrelation in open-to-close portfolio returns.

2.5.3. Summary: portfolio return autocorrelation

The following are our main findings for *portfolio* return autocorrelation:

- We reject the hypothesis that the conventional portfolio return autocorrelation is zero. In the first half of our data period, the autocorrelations are positive. In the second half of our data period, only two portfolios show significant autocorrelation, and both are negative. The positive autocorrelations can reflect any combination of NT and PPA, while the negative return autocorrelations can only reflect PPA.
- We also reject the hypothesis that the open-to-close portfolio return autocorrelation is zero. Even though this approach excludes NT, the results are qualitatively similar to those obtained with conventional returns. In the first half of our data period, the autocorrelations are positive and significant in nine of the ten size portfolios, but in the second half, only four of ten portfolios show significant autocorrelation, and all four are negative. Both the positive and negative autocorrelations can only arise from PPA.
- We find that PPA is the main source of portfolio return autocorrelation in all time subperiods and all size groups except the largest; even there, it falls just below 50%.
- We find that the conventional return autocorrelation of the SPDRs is negative and statistically significant; this could only come from PPA or BAB. We bound BAB in terms of the relative spread ratio of the SPDRs, and correct the autocorrelation to eliminate any possible negative autocorrelation arising from BAB. We find that PPA is the main source of the negative autocorrelation in the SPDR returns.
- We find that past returns of the SPDRs predict future returns of individual stocks. The autocorrelations are predominantly positive in the first half of our data period; in the second half, the significant autocorrelations are found mostly in the five smallest size cohorts and are mostly negative. These autocorrelations can only come from PPA.
- As a robustness check, we reran all autocorrelation tests using the Andrews and Kendall tests instead of the Pearson test, and obtained qualitatively similar results.[13]

3. Concluding remarks

Daily stock return autocorrelation is one of the most visible stylized facts in empirical finance. While the price discovery literature has clearly demonstrated the existence of PPA in the varying speeds of adjustment across different assets, there is no consensus in the previous literature on the relative contributions of NT, BAB, PPA, and TVRP to daily return autocorrelation.

We find compelling evidence that PPA is an important source, and in some cases the main source, of stock return autocorrelation. PPA is an important source of autocorrelation in all of our tests involving small and medium firms, and in most of our tests involving large firms. Our tests cover both individual stock return autocorrelation and portfolio return autocorrelation. We find that PPA is an important source of autocorrelation in SPDRs, a very actively traded ETF.

Our methods for separating NT, BAB, PPA, and TVRP components of stock return autocorrelation are generally applicable. These methods make use of three key ideas: theoretically signing and/or bounding these components; computing returns over disjoint return subperiods separated by a trade to eliminate NT; subdividing our data period into time-horizon subperiods to obtain independent autocorrelation measures. We also develop a technique to determine a lower bound on the proportion of autocorrelation arising from PPA.

[13] The results using the Andrews and Kendall tests may be found in Anderson et al. (2012).

We use two methods to eliminate NT. The first method computes correlations of open-to-close returns; this method can be applied to eliminate NT with other types of securities, and on other exchanges. The second method, used in computing the correlation of individual stock returns and SPDRs, computes the return of the SPDRs separately in the periods before and after the final trade of the stock; this method can be used to eliminate NT using any security which, like the SPDRs, is traded nearly continuously.

By dividing our data period into disjoint time-horizon subperiods, we obtain independent tests of the sources of autocorrelation in the different time-horizon subperiods. Aggregating the tests across time-horizon subperiods allows us to increase the statistical power of our tests, and to work around the problem that returns are correlated across stocks. Our methods for aggregating the results of the time-horizon subperiod tests can be applied to other types of securities and other exchanges.

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