Available online at www.sciencedirect.com
ScienceDirect
Journal of Empirical Finance 15 (2008) 533 – 548
Journal of EMPIRICAL FINANCE
www.elsevier.com/locate/jempfin

Excess demand and price formation during a Walrasian auction

James Eaves [a,*], Michael Melvin [b], Sandeep Mohapatra [c]

[a] University of Laval, Canada
[b] Barclays Global Investors, United States
[c] University of Alberta, Canada

Received 16 August 2006; received in revised form 25 April 2007; accepted 6 September 2007
Available online 26 September 2007

Abstract

We conduct a detailed analysis of the relationship between excess demand and the convergence of price to equilibrium during a real-world Walrasian auction, paying special attention to the size and speed of the price adjustment. Using data from the Tokyo Grain Exchange (TGE), we first show that because auctions for the various futures contracts occur sequentially, information becomes more evenly dispersed across traders as an auction sequence progresses. Then we show that excess demand is positively correlated with both the eventual price change and the speed with which price adjusts. As information becomes more evenly dispersed, the strength of these relationships weakens. Finally, though excess demand explains a large proportion of the variability of the change in price, it explains only a small proportion of the variability of the speed of adjustment.

JEL classification: D44; D50; G00; G14
Keywords: Walrasian auction; Excess demand; Price formation; Information

1. Introduction

For nearly a century, the Walrasian auction has served as the chief theoretical framework for analyzing the dynamics of price. But, despite this significance, there is nearly an absence of empirical studies of Walrasian auctions.[1] In a sense, economic practitioners have accepted a fundamental economic hypothesis – excess demand drives price to equilibrium during a Walrasian auction – without testing it in the real-world. The lack of empirical evidence on this issue, more importantly, has left unanswered several basic questions regarding the process of price discovery and the nature of

* Corresponding author. Departement de finance et assurance, Pavillon Palasis-Prince, Universite Laval, Quebec, Canada G1K 7P4.
E-mail address: james.eaves@fsa.ulaval.ca (J. Eaves).

[1] While not analyzing the dynamics of the actual price formation process, a few studies have analyzed equilibrium prices generated from a Walrasian auction, In particular, Booth and Ciner (1997), Cobos et al. (1997), and Webb (1995) analyze the volatility of equilibrium prices on the Tokyo Grain Exchange (TGE), which uses Walrasian auctions to find prices. We are aware of only one previous study related to the actual equilibrating process — Eaves and Williams (2007) use auction data from the TGE to test if the dynamics of the TGE auctions suggest traders behave competitively or not. Eaves and Williams focus on individual pledges and the subsequent reaction of provisional price. This study analyzes characteristics of the full price adjustment in response to initial excess demand.

0927-5398/$ - see front matter
doi:10.1016/j.jempfin.2007.09.003

linkages between different market variables during the equilibrium process. The paucity of empirical work, however, is not surprising, given that until recently very few studies had access to field data on Walrasian auctions.

The analysis of real-world Walrasian auctions, however, requires a framework that goes beyond Walras's original framework for analyzing market behavior. Walras's basic structure of a market involves buyers and sellers bidding for a good and an auctioneer who is guided by the imbalance or excess demand to set prices such that the market clears (Walras, 1874). In this framework informational asymmetries among traders play no role, and the evolution of available information across traders is abstracted away. Obviously, this is not the case in real-world auctions — information sets will differ across traders and evolve within successive auctions for the same or similar commodities.

Under the extended framework, the process of equilibrium may be characterized by analyzing the interaction between three variables — information, excess demand, and price. At the beginning of the process, when beliefs about intrinsic value are most divergent across the auctioneer and traders, informational asymmetries regarding the (expected) value of the asset causes a strong link between excess demand and price changes. The level of excess demand not only reflects consumption needs and supply capabilities of traders but also is a signal to the auctioneer regarding private information held by some traders regarding the value of the asset, a factor that potentially could bias the discovery of the true value of the asset. The auctioneer therefore sets price cautiously, knowing that both informed traders with private information and non-informed traders are present in the market. As information becomes more symmetrically distributed, provisional price becomes increasingly informative of underlying demand and supply conditions and the link between excess demand and the auctioneer's pricing rule weakens (Vives, 1995).

Using this framework, the overall goal of this study is to use a unique set of data on Walrasian auctions conducted on the Tokyo Grain Exchange (TGE) to empirically demonstrate Walras' original proposition regarding price formation and its link to excess demand. The TGE is an electronic futures and options exchange and is unique as being the only exchange in the world that finds prices using Walrasian tâtonnement auctions.[2] Each auction begins when an auctioneer displays a provisional price, whereupon traders submit quantity pledges to buy or sell. The auctioneer adjusts the provisional price in the appropriate direction given aggregate excess demand. An auction ends only after a provisional price, at which the cumulative pledges clear the market, is reached. Another unique characteristic of the TGE is that auctions occur periodically and sequentially throughout the trading day.

Using thousands of transcripts detailing the entire series of pledges entered by individual traders and provisional prices set by a live auction, we first establish that the dispersion information plays a role in the price discovery process — a role that evolves across successive auctions. We do so using a two simple autoregressive model of asset returns to show how informational rents to informed traders dissipate as a sequence of auctions progresses. We compliment these results with results from a PIN (Probability of Informed Trading) model that show that the probability of informed trading diminishes as a sequence of auctions progresses. After having established that informational asymmetries between traders dissipate as an auction sequence progresses, we then describe the relationship between excess demand and the amount price adjusts and report how this relationship is conditioned on the dispersion of information. Finally, we establish the link between excess demand and the speed with which price converges to equilibrium, conditional on the dispersion of information.

Our empirical results show that the amount price changes is highly correlated with the excess demand observed at the start of the auction, but this link weakens as information becomes more evenly dispersed across traders. The absolute value of excess demand increases the speed with which prices converge to equilibrium and this link also declines as information asymmetry subsides. Finally, excess demand explains a large fraction of the variability of the change in price, but the absolute value of excess demand explains only a small fraction of the variability of the speed with which prices adjust.

The paper is organized as follows. The next section provides an overview of the auction protocol at the TGE. Section 3 describes the data, empirical methodology, and results. The summary and conclusions are presented in Section 4.

2. The Tokyo Grain Exchange auctions: Context and data

The TGE is an electronic futures and options exchange listing some of the same commodities as the Chicago Board of Trade and the New York Board of Trade. However, unlike on these exchanges where futures are traded continuously and simultaneously, on the TGE futures are traded during six daily sessions of discrete auctions. During each trading session, up to five commodities are auctioned in a set sequence. Each commodity's six delivery months are also

[2] Several exchanges use mechanisms that share characteristics with a Walrasian tâtonnement auction to find opening prices (for example, in the Paris Bourse, Toronto Stock Exchange, and the Arizona Stock Exchange).

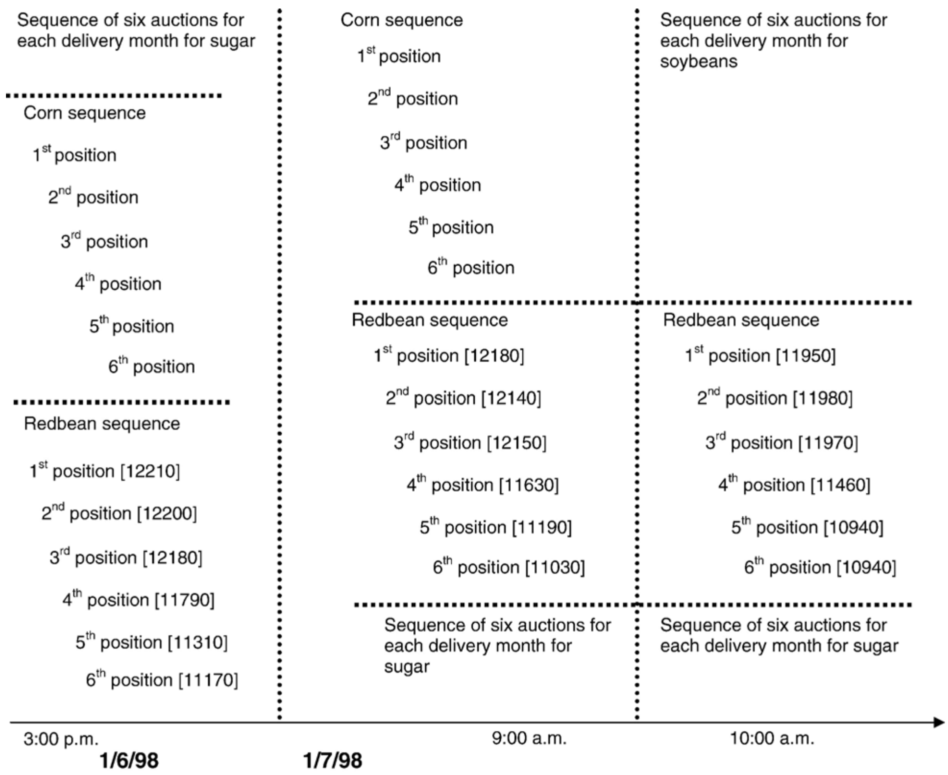

Fig. 1. Sequence of auctions (1/6/1998–1/7/1998). On the TGE, each commodity's six delivery months are auctioned in sequence, the nearest delivery month ("position") first. Trading sessions begin at 9:00 a.m., 10:00 a.m., 11:00 a.m., 1:00 p.m., 2:00 p.m., and 3:00 p.m. This figure illustrates the sequence of auctions conducted during the final trading session held on January 6th, 1998 and those held during the first two sessions of January 7th. The final price (yen) for each redbean contract is reported in brackets.

auctioned in sequence, the nearest delivery month ("position") first. Trading sessions begin at 9:00 a.m., 10:00 a.m., 11:00 a.m., 1:00 p.m., 2:00 p.m., and 3:00 p.m. and the mix of commodities and their order varies across the sessions. For four commodities, Fig. 1 illustrates the sequence of auctions conducted during the final trading session of January 6th, 1998 and the first two trading sessions of January 7th, 1998.[3] On January 7th, the TGE opened at 9:00 a.m. with an auction for the nearest corn futures contract. Seconds after completion of that auction, which typically would have taken about 1 min, the auction for the second-position corn contract began, and so on for all six delivery months. After the corn sequence was completed, the six delivery months for redbeans were auctioned in sequence, and after the redbean contracts, the six sugar contracts were auctioned in sequence. Once the auction for the sixth-position sugar contract finished, typically around 9:40, the traders would have imparted volume statistics to the TGE and contemplated the next session commencing at 10:00. Six such trading sessions are conducted each business day, the mix and order of commodities varying across sessions.

As opposed to data from continuous auction exchanges, data from the TGE allows us to identity when traders are more or less evenly informed about the value of a contract. In particular, on futures exchanges like the NYMEX or the CBOT, a number of commodities are traded continuously, either in pits or electronically, throughout the trading day. Though traders can observe a transaction prices for several contracts, the simultaneity of transactions makes it difficult, for example, for a corn trader to forecast a change in the value of a "back-month" contract by observing the price of a "nearby-month" contract. In contrast, on the TGE, contracts trade sequentially and only one auction takes place at any point in time, making causality obvious — all traders observe information that is relevant for longer maturity contracts before those auctions take place. In the empirical section we show that the implication of the sequential design is that traders start each auction more fairly informed than the last about the value of the contract.

[3] The figure explicitly illustrates the sixth positions for corn and redbeans, since those commodities are the focus of this study; however, the structure of a trading session is the same for each commodity.

Given the overall description of how auctions occur, we next turn to a more detailed description of an individual auction. Each auction begins with a live auctioneer, who is situated within the TGE building, using a computer terminal to post an initial provisional price. The level of the initial price is chosen to reflect the information revealed in the most recent auction held during the trading session. In particular, for the second through the sixth-position futures contracts, the auctioneer sets the initial provisional price equal to the final price discovered for the same contract during the previous session plus the change in price of the contract traded in the immediately preceding auction. For instance, referring to Fig. 1, the initial provisional price for the second-position redbean auction conducted during the 10:00 session was equal to the final price reached for the second-position redbean contract during the 9:00 session (12,140 yen) plus the session-to-session change in price of the first-position contract (11,950–12,180). Since first-position futures contracts are auctioned first each session, the auctioneer sets the initial provisional price of those auctions equal to the final price reached for the same contract during the previous trading session. For instance, referring to Fig. 1, the initial provisional price for the first-position redbean contract auctioned during the 10:00 session on January 7th was equal to the final price reached for the same contract during the 9:00 session (12,180 yen).

Once the initial provisional price is posted, traders use designated computer terminals to respond with pledges to buy or sell particular quantities. The individual pledges, identified as coming from futures commission merchants (FCMs) or independent traders, the resulting cumulative imbalance, and the provisional price are visible to all participants instantaneously.[4] If the initial provisional price does not clear the market, the auctioneer adjusts it, one tick of 10 yen at a time, in the direction of excess demand. The auctioneer and the traders work in real time; the auctioneer, seeing a considerable excess demand, may not wait for every pledge before adjusting the price, while the traders may adjust their pledges as often as they wish even if the auctioneer has not adjusted the price. Whenever the auctioneer adjusts the provisional price, each displayed pledge remains valid unless a trader revises it.

Table 1 shows a transcript from a TGE auction, one held during the second session on January 7, 1998, for a futures contract specifying delivery of corn at the end of March 1998. The auction's equilibrating price was 15,700 yen, after 61 s and four intervening provisional prices beginning at 15,660 yen. Ultimately, 91 contracts changed hands between nine sellers and fourteen buyers. The first column in each sub-panel indicates the time. If a time stamp is missing for a particular second (e.g., 11:19:13), no event occurred. The second column indicates the provisional price displayed by the auctioneer. The third column indicates the aggregate excess demand (total long pledges cumulatively minus total short pledges cumulatively). Column four indicates the two-letter abbreviation of the FCM entering a pledge and column five reports the pledge.

An auction ends when excess demand goes to zero when the "OK sign" is posted by the auctioneer. The last column of each sub-panel in Table 1 reports if the auctioneer is posting the OK sign or not. At 11:19:28, with an excess demand of +46 contracts, the auctioneer displayed the "OK" for the first time, indicating that he felt the provisional price was near the equilibrium price. If a pledge or combination of pledges were entered between 11:19:28 and 11:19:33 that drove excess demand to zero, the auction would have ended instantly and all cumulative pledges would have been transformed to trades at 15,660 yen. However, excess demand did not go to zero in what the auctioneer deemed a reasonable amount of time, so at 11:19:33, the auctioneer simultaneously removed the OK sign and adjusted the provisional price upward to 15,670 yen. This process of adjusting the provisional price and posting the OK sign continues for three more provisional-price attempts. Then, at 11:20:12, when the OK sign was on and excess demand was +20, trader "OC" adjusted his pledge from buy 35 to buy 15, which drove excess demand to zero and ended the auction. This particular auction took 61 s to reach equilibrium.

Table 1 illustrates that the auctioneer responds to excess demand with a lag and the number of seconds between price adjustments varies. For instance, though a +34 excess demand had emerged 9 s into the auction, the auctioneer did not increase the provisional price for another 13 s. In fact, despite the excess demand, auctioneers typically wait at least 10 s before making the first adjustment because they are aware that traders enter auctions gradually, making it common for the sign of excess demand to switch during the first few seconds of auctions. However, after the first adjustment, the auctioneer responds much more quickly to any imbalance. For the auction shown in Table 1, the series for time between the price changes, including the initial adjustment and the end of the auction, is 22, 13, 9, 9, and 8. A variable response is at least partially explained by the minimum tick size but is also explained by the auctioneer's awareness that the likelihood of an imbalance being meaningful depends on characteristics like the persistence of the imbalance, the sizes of individual pledges, the rate pledges arrive, and, perhaps, even the origin of the pledge.

[4] A FCM's pledge represents the net among orders placed by its many non-member customers, orders taken on behalf of the twenty-five or so exchange members who have opted not to rent the specialized computer terminal, and speculative orders made by its "house trader".

Table 1
A transcript of a TGE auction

Time	Prov.	ED	ID	Plg	OK
11:19:11	**15,660**	0		0	
11:19:11	15,660	1	TB	1	
11:19:12	15,660	4	SW	3	
11:19:14	15,660	−6	MJ	5	
11:19:14	15,660	−6	OC	−15	
11:19:14	15,660	−4	KN	5	
11:19:14	15,660	−4	TG	−3	
11:19:15	15,660	−3	OC	−14	
11:19:16	15,660	−2	YI	1	
11:19:18	15,660	8	OC	−4	
11:19:19	15,660	3	KY	−5	
11:19:20	15,660	34	OC	26	
11:19:20	15,660	34	OY	1	
11:19:21	15,660	36	IG	2	
11:19:22	15,660	31	YZ	−5	
11:19:22	15,660	21	YT	−5	
11:19:22	15,660	21	KU	−5	
11:19:23	15,660	17	FF	−2	
11:19:23	15,660	17	CT	−2	
11:19:24	15,660	16	ST	−1	
11:19:25	15,660	12	MM	−4	
11:19:25	15,660	17	OC	31	
11:19:27	15,660	16	NH	−1	
11:19:27	15,660	26	OC	41	
11:19:28	15,660	44	OM	18	
11:19:28	15,660	46	DO	2	
11:19:28	15,660	46		0	OK
11:19:29	15,660	31	MM	−19	OK
11:19:30	15,660	26	MJ	0	OK
11:19:33	15,660	29	IG	5	OK
11:19:33	**15,670**	29		0	
11:19:34	15,670	49	OM	38	
11:19:35	15,670	46	SW	0	
11:19:35	15,670	41	KN	0	
11:19:35	15,670	31	OC	31	
11:19:36	15,670	30	ST	−2	
11:19:37	15,670	27	OY	−2	
11:19:39	15,670	28	OC	32	
11:19:39	15,670	18	OY	−12	
11:19:39	15,670	18		0	OK
11:19:40	15,670	19	OT	1	OK
11:19:41	15,670	14	MJ	−5	OK
11:19:42	15,670	16	MU	2	OK
11:19:42	15,670	11	KN	−5	OK
11:19:46	**15,680**	**11**		0	
11:19:47	15,680	21	FJ	10	
11:19:47	15,680	16	MJ	−10	
11:19:50	15,680	14	MJ	−12	
11:19:51	15,680	14		0	OK
11:19:51	15,680	19	FF	3	OK
11:19:51	15,680	20	OC	33	OK
11:19:52	15,680	22	OC	35	OK
11:19:53	15,680	19	MM	−22	OK
11:19:53	15,680	14	CL	−5	OK
11:19:55	**15,690**	**14**		0	
11:19:57	15,690	12	FC	−2	
11:19:58	15,690	16	DO	6	

(continued on next page)

Table 1 (*continued*)

Time	Prov.	ED	ID	Plg	OK
11:20:00	15,690	17	ST	−1	
11:20:01	15,690	16	ML	−2	
11:20:01	15,690	16	NH	0	
11:20:01	15,690	16		0	OK
11:20:03	15,690	26	OM	48	OK
11:20:04	**15,700**	**26**		0	
11:20:06	15,700	21	YZ	−10	
11:20:07	15,700	20	OT	0	
11:20:11	15,700	20		0	OK
11:20:12	15,700	0	OC	15	END

The table shows a transcript for the auction conducted during the 11:00 trading session on January 7, 1998 for the corn futures contract expiring in March 1998. From left to right of each sub-panel, the columns report the time, the provisional price, the aggregate excess demand, the trader's ID, the trader's pledge, and the status of the OK signal. When excess demand is driven to zero while the OK sign is on, the auction ends and all outstanding pledges are transformed to trades at the equilibrium price. At 11:20:12, OC adjusted his pledge from buy 35 to buy 15, driving excess demand to zero while the OK sign was turned on, which caused the auction to end at a final price of 15,700 yen.

In 1997, the TGE's four actively traded commodities were, in decreasing volume, corn, soybeans, redbeans, and raw sugar. More recently, arabica and robusta coffee, non-GMO soybeans, and soymeal have become actively traded. The TGE agreed to provide us with auction transcripts, like the one shown in Table 1, from 6635 corn and 8442 redbean auctions conducted from January 1997 through February 1998. These two markets offer an interesting comparison since there is relatively more public information available for corn. In particular, the TGE's corn futures contract is nearly identical to the one traded on the Chicago Board of Trade (CBOT), differing only in contract size and delivery location, Consequently, TGE traders can refer to CBOT corn prices, and analysts' coverage of the corn market, in generally, dwarfs that of the redbean market. The redbean futures market operates only through the TGE. Redbeans are marketed in Japan primarily by a few farmer cooperatives, which hide supply information. These cooperatives and other large handlers of redbeans are typically represented by just a few FCMs. Though there are no import restrictions, the only other significant source of redbeans is China and those are delivered at a discount. Altogether, this suggests that the degree of information asymmetry across auction participants is presumably greater for redbean auctions compared to corn auctions.

3. Empirical analysis

3.1. The distribution of information across a sequence of auctions

Towards accomplishing the overall objectives discussed in the Introduction, we first show how the flow of information changes as a sequence of auctions progresses. To do so, in Table 2, we show how common proxies of market structure and the flow of information vary across the six auctions of a trading session. The table reports mean levels for auction volume, the Herfindahl-Hirschman Index (HHI), the number of traders, the absolute excess demand observed immediately before the first provisional-price change, the length of an auction in seconds, the number of adjustments made to provisional price, and the number of seconds between adjustments. The top panel reports these means for corn and the bottom for redbeans.

Several statistics in Table 2 accord with the presumptive difference in competition levels and information asymmetry across each commodity's six contract positions. For both commodities, the number of traders participating directly in an auction increases and the HHI[5] – a measure of market concentration – decreases as a trading session progresses: the HHI is about twice as high during first-position auctions compared to sixth-position auctions, indicating that individual traders become increasingly smaller relative to the market as a session progresses. Auction volume also

[5] We calculate the HHI as the sum of the squares of the market shares of the traders who participated directly in an auction — primarily future commission merchants. A trader's market share equals 100 times the trader's final trade divided by auction volume. Since at least two traders must participate in an auction for it to equilibrate, unlike the traditional HHI that ranges from 0–10,000, our index ranges from 0–20,000. For example, if only two traders participated in an auction, the index would equal $100^2+100^2=20{,}000$. With an infinite number of firms of equal size, the limiting value is zero.

Table 2
Descriptive statistics

	Auction volume	Number of traders	Herfindahl-Hirschman Index	Initial absolute excess demand	Length of auction (s)	Number of adjustments to price	Seconds between adjustments
Corn contract position							
First	87.27	24.28	4835.85	56.98	85.45	12.49	6.41
Second	143.36	29.19	4157.60	92.43	70.61	8.61	7.59
Third	239.34	34.57	3425.13	132.75	61.65	6.08	9.15
Fourth	371.79	40.05	3107.30	226.75	61.12	5.63	9.80
Fifth	567.88	47.07	2745.51	358.24	66.73	5.71	10.64
Sixth	729.81	53.11	2620.78	470.68	75.94	5.99	11.87
Redbean contract position							
First	23.29	14.27	6779.72	13.62	51.63	6.57	7.69
Second	41.98	18.73	5261.86	27.59	56.03	6.70	8.14
Third	68.02	23.02	4423.26	43.18	55.39	5.99	8.83
Fourth	109.8	27.72	3896.49	64.65	57.75	5.72	9.63
Fifth	171.53	33.30	3590.77	108.29	60.80	5.91	9.82
Sixth	232.81	38.03	3163.86	141.57	65.52	5.92	10.53

The table reports means for the absolute excess demand observed just before the first adjustment to provisional price, auction volume, the number of traders who participated directly in auctions, the Herfindahl-Hirschman Index, the length of an auction in seconds, the number of adjustments to provisional price required to equilibrate an auction, and the number of seconds between provisional-price adjustments. These statistics are reported for each futures contract position, for both the corn and the redbean markets. There are 6635 corn and 8442 redbean auction observations, from January 1997 through February 1998.

increases monotonically. For instance, corn (redbean) auction volume is about eight (ten) times higher during sixth-position auctions compared to first-position auctions, suggesting that later auctions are more liquid than earlier ones. The intrasession pattern of volume is consistent with the predictions of Foster and Viswanathan (1990). In their model, volume and depth increase as an auction sequence progresses as discretionary uniformed traders shift their trades away from early auctions, where informed trading is most intense, to later auctions. Though the strategies of informed traders may contribute to the pattern of volume shown in Table 2, the pattern is likely primarily driven by institutional characteristics of the TGE. In particular, unlike European and U.S. futures markets, where the nearby maturity dates tend to have the highest volume, in Asian markets it is common for volume to be higher for the more distant contracts.

Depth also increases as a session progresses. To see this clearly, column 4 reports the average absolute excess demand observed just before the auctioneer adjusts the initial provisional price, as he did in Table 1 at 11:19:33. Looking down the column, we see that the critical level of excess demand required to induce the auctioneer to adjust provisional price for the first time rises sharply as the session progresses. For example, on average, the auctioneer adjusts provisional price for the first time during first-position corn (redbean) auctions when absolute excess demand is around 57 (14) contracts, whereas the average is about 471 (142) contracts for sixth-position contracts. Columns 5 and 6 show that as a session progress the total amount price changes and the length of an auction decrease. The first auction for corn typically requires 12 adjustments to provisional price and 85 s to equilibrate, while the sixth-position auction requires eight adjustments and 76 s. The last column shows that the auctioneer adjusts provisional price faster during first-position auctions: during corn (redbean) auctions, the auctioneer waits an average of 6 (8) seconds between price adjustments for first-position contracts and 12 (11) seconds for sixth-position contracts. In the context of theory, Table 2 is preliminary evidence that information flows and uncertainty surrounding the value of contracts decline as a session progresses. In particular, Vives (1995) predicts that as the uncertainty surrounding the value of the asset diminishes, the auctioneer's pricing rule becomes decreasingly sensitive to pledge flow and depth increases. Subrahmanyam (1991) predicts that when information is more evenly dispersed across traders, prices aggregate information more quickly.

Consistent with the presumption that the structure of the corn and redbean market is different, volume is around three-times higher and nearly twice as many traders participate during corn auctions, yet corn auctions take only slightly longer to equilibrate. Moreover, the HHI is between 20% and 40% higher during redbean auctions, depending on the contract position. Looking across the six redbean positions, we see that there is less difference in the required number of price adjustments relative to the difference across corn auctions. On average, first-position redbean auctions require only one more adjustment to equilibrate than sixth-position auctions. Also, the mean length of a redbean auction tends to increase as a session progresses: first-position redbean contracts require an average of 52 s to equilibrate, while sixth-position contracts require 66 s. Though the rate the auctioneer adjusts provisional price increases in both markets as the session progresses, the rate the adjustment rate increases is much higher for corn: for corn, the provisional price is adjusted about 85% faster during first-position auctions than during sixth-position auctions, whereas it is adjusted about 37% faster during first-position redbean auctions compared to sixth-position redbean auctions.

3.2. The distribution of information across traders

Above we assert that the structure imposed by the TGE's sequential design of auctions allows all traders to observe information that is relevant for longer maturity contracts before those auctions take place. An implication is that traders become more symmetrically informed as a trading session progresses. Table 2 provides initial support for this assertion. We can illustrate this more precisely by regressing a future contract's session-to-session return against one of its own lags and against the return observed for the most recent auction for the same commodity. If we find that the predictive power of the model increases substantially as the contract position increases, then we can conclude that the average trader's belief about value becomes more accurate as a trading session progresses. It is simplest to clarify the regression by referring to a specific situation in Fig. 1. For instance, the return observed for the sixth-position redbean contract during the 10:00 session is modeled as a function of one of its own lags (the return observed for the sixth-position redbean contract during the 9:00 session) and the return observed for the fifth-position redbean contract during the 10:00 session. For first-position contracts, the most recent auction for the same commodity is the final auction of the commodity's previous trading session. For instance, we model the return observed for the first-position redbean contract during the 10:00 session as a function one of its own lags (the return observed for the first-position redbean contract during the 9:00 session) and the return observed for the sixth-position redbean contract during the 9:00 session[6].

The results are reported in Table 3. Referring to the results for first-position corn contracts, we see that the coefficient on the return observed for the sixth-position corn contract during the previous trading session is 0.319 and the R^2 is 0.04. Referring to the results for sixth-position corn contracts, we see that the coefficient on the return observed for the fifth-position contract during the same trading session is 0.895 and the R^2 is 0.86.[7] The findings give strong support to the hypothesis that private information becomes less and less important relative to public information and trader expectations becomes more evenly dispersed as an auction sequence progresses.

The results for the redbean regressions display a similar upward-sloping pattern, but both the estimated coefficient and the R^2 climb at a slower rate. Referring to the results for first-position redbean contracts, we see that the coefficient on the return observed for the sixth-position redbean contract during the previous trading session is 0.482 and the R^2 is 0.19. Referring to the results for sixth-position redbean contracts, we see that the coefficient on the return observed for the fifth-position contract during the same trading session is 0.82 and the R^2 is 0.71. The fact that the R^2 in Table 3 increases at a slower rate across the redbean regressions is evidence that information is impounded into price more slowly in the redbean market, or information dispersion is less rapid compared to the corn market. However, it is difficult to pin down the reasons for this difference. One explanation is that because information acquisition costs are likely higher in the redbean market, informed traders can more effectively spread-out their trades across a redbean trading session (Foster and Viswanathan, 1990). Another explanation is that the relative scarcity of news surrounding the redbean market makes it more difficult for traders to agree on the value of contracts.

Another way to demonstrate that traders become more symmetrically informed as a session progresses is to examine the forecast error of an auction's initial provisional price. If the initial provisional price becomes a better forecast of the equilibrium price as an auction sequence progresses, then later auctions are characterized by less uncertainty. This is explored by examining the absolute forecast error of the following model:

$$|P^{\mathrm{F}} - P^{1}| = \alpha + \beta_1 \mathrm{ses1} + \sum_{i=2}^{6} \beta_i \mathrm{dum}_i + \varepsilon \tag{1}$$

[6] We experimented with including more lags of a contract's own returns and the returns for the other intervening auctions, but doing so had little effect on the results.

[7] Since during a Walrasian tâtonnement auction no transactions may take place until an equilibrium price is reached, predictability of a contract's price change at the start of an auction does not imply an arbitrage opportunity.

Table 3
The predictability of the change in price

	Future contract position					
	First	Second	Third	Fourth	Fifth	Sixth
Corn						
Constant × 100	0.020	0.000	0.005	0.009	−0.012	0.001
	(0.78)	(0.01)	(0.43)	(0.85)	(1.12)	(0.09)
Lagged own return	−0.201	−0.091	−0.074	−0.070	−0.072	−0.054
	(4.40)	(5.24)	(6.06)	(5.38)	(5.49)	(4.68)
Return observed for the previous auction for the same commodity	0.319	0.795	0.949	0.867	0.888	0.895
	(6.48)	(47.64)	(75.28)	(69.43)	(69.65)	(80.94)
Observations	997	987	969	976	972	943
R-squared	0.04	0.67	0.84	0.82	0.82	0.86
Redbeans						
Constant × 100	0.005	0.012	−0.002	0.001	−0.009	−0.004
	(0.35)	(0.94)	(0.17)	(0.16)	(1.01)	(0.49)
Lagged own return	−0.153	−0.175	−0.110	−0.096	−0.078	−0.100
	(6.20)	(8.88)	(6.94)	(7.17)	(5.30)	(7.01)
Return observed for the previous auction for the same commodity	0.482	0.700	0.794	0.840	0.815	0.807
	(19.63)	(32.51)	(48.70)	(62.77)	(54.81)	(60.12)
Observations	1584	1586	1585	1577	1571	1512
R-squared	0.19	0.40	0.60	0.71	0.66	0.71

The table reports results from regressing a futures contract's session-to-session return against one of its own lags and against the return observed for the most recent auction for the same commodity, which is public information at the start of an auction. For example, for a second-position futures contracts, the most recent auction for the same commodity is the auction for the first-position futures contract held the same trading session. For a third-position futures contract it is the auction for the second-position contract and so on for the fourth through sixth-position contracts. For the first-position futures contract, the most recent auction for the same commodity is the auction for the sixth-position contract held the previous trading session. The data include session-to-session returns observed from January 1997 through February 1998. Absolute values of *t*-statistics are in parentheses.

where P^{F} is the final equilibrium price of the *i*-th position contract auctioned during a session, P^{1} is the auction's initial provisional price, ses1 is a dummy variable indicating if the auction occurred during the first session of the day, and dum_i are dummy variables indicating the contract position, excluding the one indicating a first-position contract.

Estimation results are reported in Table 4. Corn and redbean auctions held during the first session of each day are seen to have absolute forecast errors that are 13.7 and 12.3 yen higher, respectively, than auctions held during later sessions. Regarding the contract positions, the coefficients for the dummy variables indicate that forecast errors fall as a trading session proceeds. For instance, second-position corn (redbean) auctions have average forecast errors of 37.7 (2.8) yen lower than first-position auctions while sixth-position auctions have average forecast errors of 65.5 (15.2) yen lower than the first-position auctions. Consistent with the hypothesis that the equilibrium is relatively more difficult to reach during a redbean auction, we see that the rate the forecast error decreases is lower for redbeans. For example, relative to the mean, the forecast error tends to be 42% lower during second-position corn auctions, compared to 7% lower during second-position redbean auctions.

3.3. Probability of informed trading across a sequence of auctions

Next, we estimate how the probability of informed trading varies as a session progresses. A measure of the probability of informed trading (PIN) that is used in a wide range of applications in market microstructure, corporate finance, and asset pricing is a methodology developed by Easley, Kiefer, O'Hara, and Paperman (EKOP) (1996). The PIN methodology assumes that bids (in our case, pledges) arrive as Poisson processes. Uninformed or liquidity-motivated bids arrive at rate ε per unit of time. We use seconds as the time unit. Private-information-motivated bids arrive at rate μ per second. All arrival rates are assumed to be independent. At the start of each auction session, an information signal is exogenously generated. The probability of there being an informative signal is denoted as α so that the probability of no information is $(1-\alpha)$. The probability of bad news is denoted as δ with the probability of good news $(1-\delta)$. The basic idea is that for sessions with good news, there will be more buy bids with arrival rates $\varepsilon+\mu$, while sell bids arrive at rate ε. Bad news sessions will have more sell bids with arrival rates $\varepsilon+\mu$, while buy bids arrive at rate ε. Auctions with no news will have arrival rates of ε for both buys and sells so there should be an equal number of bids on each side of the market.

Table 4
Absolute forecast error of the initial provisional price

	Corn	Redbeans
Constant	90.592	42.096
	(51.93)	(44.32)
ses1	13.745	12.344
	(8.54)	(12.11)
Position 2	−37.727	−2.818
	(15.62)	(2.13)
Position 3	−59.776	−9.817
	(24.64)	(7.40)
Position 4	−64.741	−15.067
	(26.74)	(11.35)
Position 5	−65.266	−13.397
	(26.89)	(10.08)
Position 6	−65.500	−15.176
	(26.85)	(11.35)
R-squared	0.17	0.04

The table reports results from estimating:

$$|P^{F} - P^{1}| = \alpha + \beta_1 \text{ses1} + \sum_{i=2}^{6} \beta_i \text{dum}_i + \varepsilon$$

where P^F is the final equilibrium price of the i-th position contract auctioned during a session, P^1 is the auctioneer's initial provisional price announced at the start of the auction, ses1 is a dummy variable indicating if the auction occurred during the first session of the day, and dum_i are dummy variables indicating the contract position. There are 6635 corn and 8442 redbean auction observations. Absolute values of t-statistics are in parentheses.

The auctioneer knows the unconditional probabilities but does not know the exogenous information received by the informed traders. At the start of each day, the auctioneer has prior beliefs reflected in the vector $P(0)$ as:

$$P(0) = \left[P_{\rm n}(t), P_{\rm b}(t), P_{\rm g}(t)\right] = [1-\alpha, \alpha\delta, \alpha(1-\delta)] \tag{2}$$

where $P_{\rm n}$ represents the probability of no news; $P_{\rm b}$, bad news; and $P_{\rm g}$ good news. As bids arrive, beliefs are updated in a Bayesian manner. Let S_t represent the event of a sell bid arriving at time t and B_t represent a buy bid. It is known that buy and sell bids follow one of three Poisson processes each auction: more buy bids for good news auctions; more sell bids for bad news auctions; and fewer bids for auctions with no news. So the likelihood function can be specified as a mixing model with the weights on the state of news being the probability of observing the daily data. Observing the order arrival process allows the estimation of a four-parameter model, with the parameter vector $\theta=(\alpha,\delta,\varepsilon,\mu)$. The likelihood function is:

$$\begin{aligned} L((B,S)|\theta) = {} & (1-\alpha)\left\{e^{-\varepsilon T}\frac{(\varepsilon T)^B}{B!}e^{-\varepsilon T}\frac{(\varepsilon T)^S}{S!}\right\} \\ & +\alpha\delta\left\{e^{-\varepsilon T}\frac{(\varepsilon T)^B}{B!}e^{-(\mu+\varepsilon)T}\frac{((\mu+\varepsilon)T)^S}{S!}\right\} \\ & +\alpha(1-\delta)\left\{e^{-(\mu+\varepsilon)T}\frac{((\mu+\varepsilon)T)^B}{B!}e^{-\varepsilon T}\frac{(\varepsilon T)^S}{S!}\right\} \end{aligned} \tag{3}$$

where T is the number of time intervals in each auction. Estimation requires data on the number of buy and sell bids in each auction.[8] Once the parameters are estimated, the probability of informed trading or PIN is found as:

$$\text{PIN} = \frac{\alpha\mu}{\alpha\mu + 2\varepsilon}. \tag{4}$$

[8] Tyler Henry and Joachim Grammig generously provided their PIN programs so that we could modify them for our use.

The implementation of the PIN estimation for the auction data is carried out as follows. The data employed are the number of buy and sell pledges at the auctioneer's initial provisional price for each auction and time T is the duration, in seconds, that the initial price is posted. A practical issue related to the computation of the likelihood function is that as the number of buys and sells increases, the likelihood value gets numerically unstable and is slow to compute. In addition, if starting values are far from the maxima, convergence problems may result. To deal with these issues, estimation is carried out in a two-step process where first, Stirling's factorial approximation is used to obtain initial parameter estimates, which are, in turn, used as starting values in the exact computation of the likelihood function. Finally, the delta method is used to compute the standard errors of the estimated parameters.

We estimate a PIN for each session/position combination over the entire data set. Estimation results are reported in Table 5. The table reports the PIN estimates and standard errors with rows for sessions and contract positions in the columns. The highest probability of informed trading occurs during the first auction of each day — the auction for the first-position contract held during the 9:00 a.m. session. The PIN estimate equals 0.419 for corn auctions and 0.251 for redbeans. Within each corn auction session, the PIN generally falls as the auctions proceed across the following contracts. For redbean auctions, the pattern is not as regular in terms of monotonic decrease as in the case of corn. In combination with the results reported in the previous two tables, Table 5 suggests that the adverse selection problem faced by corn traders is generally dropping steadily from the first-position auction to the sixth, but it is more persistent in the case of redbeans.

Previous studies[9] have provided evidence that there is more informed trading during the start of a trading period compared to the end. The results reported in Table 5 make two contributions. First, the TGE auctions more closely resemble the sequence-of-auctions environment utilized by theory. Second, previous studies analyze data from continuous auctions, so the TGE data offer the first opportunity to observe these patterns on an exchange that uses a fundamentally different price discovery mechanism, providing evidence that the pattern is robust to the trading mechanism.

3.4. Excess demand and the change in price

The purpose of the analysis up to this point was to provide evidence that information asymmetry decreases as a session progresses. For the remainder of the paper, we describe the relationship between excess demand and the subsequent price effect and report how this relationship changes as the trading session progresses, that is, as information gets more evenly dispersed across traders.

First, we estimate, across contract positions, the price impact of excess demand. For each auction, we regress the change in price between the initial and final prices against the excess demand observed just before the auctioneer adjusted the initial provisional price. Specifically, for each combination of contract-position i and session s, a separate regression was estimated as:

$$P_{i,s} - P^{*}_{i,s} = \alpha + \beta \mathrm{ED}_{i,s} + e_{i,s} \tag{5}$$

where $\mathrm{ED}_{i,s}$ represents excess demand, $P_{i,s}$ is the final price, and $P^{*}_{i,s}$ is the initial provisional price of the auction. Results are reported in Table 6A for corn and Table 6B for redbeans. The price impact of excess demand is uniformly higher for first-position auctions and then falls steadily as each session proceeds. In addition, the first session/first-position contract auction has the highest price impact coefficient.

Below the R-squared we report the standard deviation of excess demand and we see that the typical order imbalance increases with the contract position. For instance, it is about 72 contracts for the first-session/first-position corn contract auction and 332 for the first-session/sixth-position auction. It is about 14 contracts for the first session/first-position redbean contract and 260 for the first session/sixth-position redbean contract. The last row of each sub-panel reports the forecasted price impact of a one-standard-deviation imbalance and shows that the impact decreases substantially as a trading session progresses. Between the first and last auctions of the 9:00 a.m. corn session, the price impact decreases from about 105 yen to 10 yen. Between the first and last auctions of the 9:00 a.m. redbean session, the price impact decreases from about 53 yen to 16 yen.[10] The results are consistent with the previous tables and with Vives (1995) who, once again, predicts that as the uncertainty surrounding the value of the asset diminishes, the auctioneer's pricing rule becomes decreasingly sensitive to pledge flow.

[9] Two examples are Madhavan, Roomans, and Richardson (1997) and Foster and Viswanathan (1993).

[10] To examine the robustness of these results, the models were reestimated with volume included as an explanatory variable. Conditioning on volume, the coefficients on excess demand were changed only slightly and none of the qualitative conclusions were affected.

Table 5
Probability of informed trading

Session	Futures contract position					
	First	Second	Third	Fourth	Fifth	Sixth
Corn						
9:00 a.m.	.419	.243	.162	.171	.162	.158
	(.03)	(.02)	(.01)	(.01)	(.01)	(.01)
11:00 a.m.	.235	.186	.144	.148	.155	.150
	(.02)	(.02)	(.02)	(.01)	(.01)	(.01)
1:00 p.m.	.285	.214	.159	.172	.156	.141
	(.03)	(.02)	(.01)	(.01)	(.01)	(.01)
3:00 p.m.	.246	.215	.151	.136	.142	.136
	(.02)	(.01)	(.01)	(.01)	(.01)	(.01)
Redbeans						
9:00 a.m.	.251	.223	.212	.185	.199	.197
	(.02)	(.02)	(.02)	(.02)	(.01)	(.01)
10:00 a.m.	.188	.234	.268	.212	.197	.200
	(.03)	(.03)	(.02)	(.02)	(.02)	(.01)
11:00 a.m.	.214	.249	.228	.224	.190	.206
	(.02)	(.02)	(.02)	(.02)	(.02)	(.01)
1:00 p.m.	.215	.218	.210	.173	.169	.184
	(.02)	(.03)	(.02)	(.02)	(.01)	(.02)
2:00 p.m.	.169	.220	.207	.212	.204	.209
	(.03)	(.02)	(.02)	(.02)	(.02)	(.02)
3:00 p.m.	.203	.130	.191	.207	.189	.214
	(.02)	(.04)	(.02)	(.01)	(.01)	(.01)

The table contains estimates of the probability of informed trading (PIN) estimated using the method of Easley, Kiefer, O'Hara, and Paperman (1996). Estimates are reported for each trading session and each futures contract position. Standard errors are estimated using the delta method and reported in parentheses.

3.5. Excess demand and the speed of convergence

Next, we analyze how excess demand affects the speed with which price converges to equilibrium. An examination of this hypothesis first requires a measure of speed. In a continuous auction setting, approaches for measuring adjustment speed vary as it is unclear when price reaches equilibrium. For example, Ederington and Lee (1995) investigate the speed with which prices on futures markets adjust to macroeconomic announcements. Their measure of the amount of time it takes price to equilibrate is the time it takes for volatility to return to normal levels following an announcement. Kabir and Vermaelen (1996) estimate how new rules on the Amsterdam Stock Exchange affect the time it takes price to impound earnings information. Their estimate of the amount of time is the number of days it took for daily returns to cumulate to the total excess returns observed over the 40 day period leading up to an announcement. Another approach is to use a method like vector autoregression to forecast the amount of time it takes price to fully adjust following a volume or information shock (e.g., Hasbrouck, 1991; Dufour and Engle, 2000). Yet, in any instance when a parametric approach is used to measure adjustment speed, the measurement will be dependent on the particular specification.[11]

In contrast to continuous auctions, rather than lasting a predetermined amount of time, a TGE auction lasts as long as it takes to find a price that drives the imbalance to zero. Consequently, the TGE data offer an obvious measure of the speed with which price converges to equilibrium.[12] In particular, we measure speed as the number of price changes per second between the first adjustment to provisional price and the end of the auction.[13]

[11] For a more detailed discussion of the shortcomings of using a vector autoregression to analyze price discovery, see Lehmann (2002). For a recent review of parametric methods and their deficiencies, see Theobald and Yallu (2004).

[12] Auctions that hit price move limits before an equilibrium price could be reached (576 corn and 286 redbean auctions) were excluded from the analysis.

[13] We exclude the number of seconds it takes the auctioneer to make his first adjustment, since, as discussed above, he typically gives traders a minimum amount of time to enter their first pledge before he adjusts the initial provisional price.

Table 6
Price impact of excess demand

	First position	Second position	Third position	Fourth position	Fifth position	Sixth position	First position	Second position	Third position	Fourth position	Fifth position	Sixth position
A. Corn	*9:00 a.m. trading session*						*11:00 a.m. trading session*					
Constant	0.043	−5.107	−4.051	−1.536	−1.203	−4.207	−2.869	2.260	0.510	0.499	1.351	−3.590
	(0.01)	(1.14)	(2.03)	(0.83)	(0.69)	(2.54)	(0.53)	(0.76)	(0.25)	(0.29)	(0.89)	(1.98)
$ED_{i,s}$	1.463	0.555	0.184	0.118	0.072	0.044	1.278	0.405	0.198	0.093	0.064	0.048
	(18.14)	(17.28)	(15.03)	(15.64)	(16.03)	(14.23)	(16.66)	(17.21)	(16.00)	(15.85)	(18.75)	(16.24)
Observations	269	263	262	264	260	259	268	262	256	258	259	252
R-squared	0.55	0.53	0.46	0.48	0.50	0.44	0.51	0.53	0.50	0.50	0.58	0.51
S.D.	71.52	100.38	108.90	152.85	233.77	332.29	48.91	89.59	109.56	195.00	303.19	384.54
Forecast	104.68	50.61	15.99	16.50	15.63	10.41	59.64	38.54	22.20	18.63	20.76	14.87
	1:00 p.m. trading session						*3:00 p.m. trading session*					
Constant	0.467	−3.153	−0.058	−2.981	−2.519	0.184	2.251	−3.149	−0.762	−1.495	−2.44	−1.879
	(0.10)	(0.99)	(0.02)	(1.43)	(1.32)	(0.09)	(0.50)	(1.02)	(0.35)	(0.86)	(1.39)	(0.94)
$ED_{i,s}$	1.339	0.564	0.198	0.100	0.072	0.064	1.221	0.425	0.220	0.114	0.068	0.051
	(17.26)	(14.95)	(10.30)	(12.35)	(13.60)	(13.82)	(18.47)	(16.27)	(16.70)	(17.43)	(17.26)	(14.08)
Observations	260	251	245	247	244	237	255	245	241	243	239	234
R-squared	0.54	0.47	0.30	0.38	0.43	0.45	0.57	0.52	0.54	0.56	0.56	0.46
S.D.	47.31	56.46	99.12	179.55	238.83	262.64	49.16	85.54	110.84	178.93	279.90	338.64
Forecast	63.81	28.69	19.57	14.97	14.68	16.99	62.27	33.21	23.62	18.90	16.59	15.39
B. Redbeans	*9:00 a.m. trading session*						*10:00 a.m. trading session*					
Constant	7.237	−2.898	2.208	−1.722	−0.520	−5.616	−1.868	−1.842	−0.293	0.647	3.090	−0.076
	(1.83)	(0.92)	(0.76)	(0.80)	(0.21)	(2.08)	(0.61)	(0.65)	(0.13)	(0.32)	(1.77)	(0.05)
$ED_{i,s}$	3.238	1.205	0.438	0.306	0.181	0.085	2.502	1.083	0.501	0.303	0.202	0.182
	(15.92)	(18.31)	(12.99)	(14.48)	(13.30)	(9.86)	(13.33)	(13.03)	(12.60)	(12.43)	(14.61)	(16.88)
Observations	275	278	278	278	276	274	277	276	276	275	273	273
R-squared	0.48	0.55	0.38	0.43	0.39	0.26	0.39	0.38	0.37	0.36	0.44	0.51
S.D.	14.28	36.87	69.42	74.83	125.98	259.89	13.50	25.50	43.03	60.66	93.87	100.34
Forecast	53.48	41.53	32.62	21.17	22.28	16.47	31.90	12.77	12.48	13.68	15.34	17.01
	11:00 a.m. trading session						*1:00 p.m. trading session*					
Constant	−7.732	0.16	−0.242	1.895	−1.076	−1.546	2.525	−0.078	−3.226	−0.015	−3.436	−1.913
	(2.52)	(0.06)	(0.12)	(1.13)	(0.62)	(1.00)	(0.67)	(0.03)	(1.24)	(0.01)	(1.88)	(1.01)
$ED_{i,s}$	1.249	0.959	0.506	0.306	0.216	0.144	1.513	0.974	0.545	0.266	0.208	0.156
	(14.54)	(12.78)	(13.83)	(14.81)	(13.99)	(14.58)	(9.18)	(14.18)	(10.12)	(10.56)	(13.39)	(12.52)
Observations	274	271	271	273	273	268	270	265	263	262	265	252
R-squared	0.44	0.38	0.42	0.45	0.42	0.44	0.24	0.43	0.28	0.30	0.41	0.39
S.D.	34.22	29.01	43.74	62.42	81.23	108.92	20.33	30.46	37.11	59.94	84.66	99.99
Forecast	35.01	27.98	21.89	21.00	16.47	14.14	33.29	29.59	17.00	15.93	14.17	13.69
	2:00 p.m. trading session						*3:00 p.m. trading session*					
Constant	−2.924	3.574	3.751	−1.761	−1.312	1.38	−5.658	4.947	4.247	−1.271	−2.689	−2.310
	(1.05)	(1.54)	(1.82)	(1.19)	(0.72)	(0.78)	(1.85)	(1.90)	(1.84)	(0.59)	(1.18)	(1.19)
$ED_{i,s}$	1.688	1.093	0.557	0.400	0.206	0.123	2.372	0.765	0.391	0.270	0.173	0.123
	(12.79)	(17.55)	(13.66)	(18.94)	(14.33)	(11.86)	(13.60)	(12.14)	(11.25)	(12.49)	(14.27)	(13.21)
Observations	269	264	263	262	263	250	269	255	254	253	247	239
R-squared	0.38	0.54	0.42	0.58	0.44	0.36	0.41	0.37	0.33	0.38	0.45	0.42
S.D.	18.62	30.05	39.13	51.32	93.00	127.15	13.32	32.87	52.97	75.91	144.11	152.50
Forecast	28.50	36.42	25.55	18.77	17.85	17.02	25.94	30.09	24.96	19.22	22.24	16.45

The table reports coefficient estimates from the following model: $P_{i,s} - P^*_{i,s} = \alpha + \beta ED_{i,s} + e_{i,s}$, where the dependent variable is the change in price from the initial provisional price to the final market-clearing price, and the explanatory variable is the excess demand, $ED_{i,s}$, measured as buy pledges minus sell pledges received at the initial provisional price. The last two rows of each sub-panel report the standard deviation of excess demand and the forecasted price change for a one-standard-deviation imbalance.

Table 7
Speed of adjustment regression

	Corn	Redbeans
9:00	−0.01305	0.00191
	(7.99)	(1.49)
Third position	−0.01132	−0.00708
	(4.03)	(4.07)
Fourth position	−0.00830	−0.01247
	(3.04)	(6.78)
Fifth position	−0.01086	−0.01164
	(3.92)	(6.32)
Sixth position	−0.01493	−0.01332
	(5.33)	(6.99)
NP/sec (auction-1)	0.19689	0.22758
	(14.19)	(18.87)
NP/sec (auction-2)	0.08426	0.09635
	(6.07)	(8.16)
NP/sec (auction-3)	0.04627	0.05538
	(3.63)	(4.72)
NP/sec (auction-4)	0.04003	0.05193
	(3.26)	(4.47)
NP/sec (auction-5)	0.03778	0.02970
	(2.96)	(2.61)
NP/sec (auction-6)	−0.01962	−0.01116
	(1.44)	(0.98)
Order flow	−0.00002	−0.00004
	(13.48)	(10.90)
Abs. ED	0.00012	0.00026
	(6.64)	(6.44)
Abs. ED at 9:00	0.00001	0.00001
	(2.04)	(0.96)
Abs. ED position 3	−0.00004	−0.00013
	(2.00)	(2.95)
Abs. ED position 4	−0.00008	−0.00014
	(4.36)	(3.17)
Abs. ED position 5	−0.00008	−0.00017
	(4.60)	(4.18)
Abs. ED position 6	−0.00008	−0.00019
	(4.60)	(4.78)
Constant	0.07089	0.06247
	(20.89)	(23.63)
Observations	4444	7076
R-squared	0.25	0.18
R2 with only ED	0.10	0.05

Table reports results from estimating:

$$\frac{\text{NP}}{\text{sec}_a} = \alpha_1 + \alpha_2 9:00 + \sum_{i=3}^{6} \alpha_i P_i + \sum_{i=1}^{6} \beta_i \frac{\text{NP}}{\text{sec}_{a-1}} + \beta_1 \text{Flow}_a + \beta_1 \text{ED}_a + \sum_{i=3}^{6} \delta_i \text{ED}_a{*}P_i + \varepsilon_a$$

Where NP/sec is the number of price adjustments per second following the first adjustment to provisional price, 9:00 is a dummy indicating if the auction occurred during the 9:00 trading session, P_i is a dummy indicating if the auction was for the i-th position contract, Flow_a is the order flow occurring before the first adjustment to provisional price, ED_a is the imbalance observed just before the first provisional-price adjustment. The last row of the table reports the R-squared of the regression when only ED_a and the interaction terms are included. White heteroskedasticity-consistent standard errors are estimated. Absolute values of t-statistics are in parentheses. There are 4444 corn auction observations and 7076 redbean auction observations.

Next, we model the effect of the absolute value of excess demand on the speed of price adjustment, conditioning the effect on contract position and liquidity, as:

$$\frac{\mathrm{NP}}{\sec_a} = \alpha_1 + \alpha_2 9:00 + \sum_{i=3}^{6} \alpha_i P_i + \sum_{i=1}^{6} \beta_i \frac{\mathrm{NP}}{\sec_{a-1}} + \beta_1 \mathrm{Flow}_a + \beta_1 \mathrm{ED}_a + \sum_{i=3}^{6} \delta_i \mathrm{ED}_a{*}P_i + \varepsilon_a \tag{6}$$

where $\frac{\mathrm{NP}}{\sec_a}$ denotes the number of price changes per second following the first adjustment to provisional price during auction a, 9:00 is a dummy variable indicating if the auction occurred during the 9:00 trading session, P_i is a dummy variable indicating if the auction was for the i-th position contract, ED_a is the absolute value of excess demand observed just before the first provisional-price adjustment. To account for liquidity affects, we include Flow_a, the order flow (buy pledges + sell pledges) occurring before the first provisional-price adjustment. We index auctions by the order in which they occurred and include as independent variables the speed provisional price adjusted during the six previous auctions. In other words, $a-1$ does not indicate the last auction for the same contract, but instead the most recent auction for the same commodity. For instance, for a fifth-position contract auction, $\frac{\mathrm{NP}}{\sec_{a-1}}$ is the speed price adjusted during the auction for the fourth-position contract that ended moments earlier. Since there are six contract positions for corn and redbeans, $a-6$ is the speed provisional price adjusted during the last auction for the same contract.

Eq. (6) is estimated using all auctions for second through sixth-position contracts that had at least one provisional-price adjustment. We drop first-position auctions since the structure and rules of the exchange suggest that the relationship between excess demand and provisional price may be substantially different during those auctions. First, first-position auctions follow at least 30 min of no trading in that commodity, whereas the other auctions for the same commodity occur seconds after one another. This trading halt leads to the accumulation of more information between first-position auctions compared to the other contract positions. Further, because the initial provisional price for first-position auctions is constrained to equal the market clearing price reached the last time the contract was traded, the initial price does not reflect the public information that was revealed in the mean time. On the other hand, since the initial prices of the commodity's subsequent auctions are set to reflect the price changes observed during the previous auctions for the other contracts, their initial prices reflect this public information. After dropping first-position auctions, we are left with 4444 corn auctions and 7076 redbean auctions.

Results from estimating Eq. (6) are reported in Table 7. Standard errors are estimated using the White heteroskedasticity-consistent covariance matrix and t-statistics associated with each coefficient are reported in parentheses. The estimation results are similar for both markets. The conditional average speed of adjustment is 0.07 adjustments per second for corn and 0.06 for redbeans. The coefficient on the 9:00 dummy variable indicates that the adjustment speed is − 0.013 slower during the first session of the day for corn. The coefficients on the contract position dummies show that the speed of adjustment declines as a trading session progresses. The results also show that despite the fact that the auctioneer sets the initial price to reflect public information, the speed with which provisional price adjusts is positively correlated with the speed of adjustment observed during the five previous auctions. Nonetheless, the speed of adjustment is not related to the speed price adjusted the last time the contract traded, suggesting there is no information spillover across auctions for the same contract. The coefficient on Flow_t is negative, which suggests that increased liquidity reduces the speed with which price adjusts.[14]

The coefficient on ED_a is positive and significant for both commodities, but the magnitude for redbeans (0.00026) is more than twice the magnitude for corn (0.00012). Finally, for both commodities, the impact of absolute excess demand on the speed of adjustment decreases as the trading session progresses. The last two rows of the table report the R^2 for the model and the R^2 when only ED_a and the position/ED_a interaction variables are included. Surprisingly, by itself, the level of excess demand explains only 0.10 of the variability of the speed of adjustment for corn and only 0.05 for redbeans.

4. Summary and conclusions

Given the central role of the Walrasian auction in economic thought, it is surprising that so little attention has been devoted to the empirical properties of a real-world Walrasian auction. In the present study, we use data from the Tokyo Grain Exchange (TGE), a futures and options exchange that uses Walrasian auctions to find transaction prices, to ask how the excess demand observed at the start of an auction affects how much and how quickly price adjusts. The unusual structure of the TGE allows us to also ask how these relationships are sensitive to the dispersion of information across traders.

[14] Dufour and Engle (2000) define a market as liquid if a trade's impact on the price is relatively small and the price adjusts relatively slowly.

On the TGE, auctions for a commodity's various delivery months are conducted sequentially and periodically. Using means for variables commonly considered proxies for the intensity of the flow of information, we first show that the flow of information decreases as an auction sequence progresses. Then, using estimates of the probability of informed trading (PIN) and a simple forecasting model, we show that the sequential design of auctions also causes information to become more evenly dispersed across traders as an auction sequence progresses.

After describing the distribution of information across an auction sequence, we show that the amount price adjusts during an auction is highly correlated to the excess demand observed at the start of an auction, but the link weakens as an auction sequence progresses. The absolute value of excess demand is positively correlated with the speed with which price adjusts and this link also weakens as information asymmetry subsides. Though, the initial excess demand is a good predictor of the amount provisional price will adjust during an auction, the level of excess demand is a relatively poor predictor of the speed with which provisional price will adjust.

The differences in the impact of excess demand on the magnitude of a price change across contract positions are consistent with market-microstructure theory. For instance, Vives (1995) predicts that as the uncertainty surrounding the value of the asset diminishes, provisional prices become increasingly informative and the auctioneer's pricing rule becomes decreasingly sensitive to pledge flow. Admati and Pfleiderer (1988) predict that when traders observe similar information signals, individual orders should offer relatively little to the existing pool of information. Moreover, presuming informed traders are more active early in an auction sequence, when their informational advantage is greatest, the results for the speed of adjustment are consistent with Holden and Subrahmanyam (1992), who predict that price will converge to equilibrium more quickly when informed traders are active. Because the redbean contract is unique to the TGE, while the corn contract is nearly identical to the one traded on the CBOT, it is likely that the ratio of public-to-private information is lower for redbeans, implying informed trades are more important on that market. In the context of Holden and Subrahmanyam (1992), this may explain why the magnitude of the impact of absolute excess demand on the speed of adjustment is greater for redbean auctions.

References

Admati, A.R., Pfleiderer, P., 1988. A theory of intra-day trading patterns: volume and price variability. Review of Financial Studies 1, 3–40.

Booth, G., Ciner, C., 1997. International transmission of information in corn futures markets. Journal of Multinational Financial Management 7, 175–187.

Cobos, J., Dhillon, U., Lasser, D., Watanabe, T., 1997. Volatility, information, and double versus walrasian auction pricing in US and Japanese futures markets. Journal of Banking and Finance 21, 1045–1061.

Dufour, A., Engle, R., 2000. Time and the price impact of a trade. Journal of Finance 55, 2467–2497.

Eaves, J., Williams, J., 2007. Walrasian tâtonnement auctions on the Tokyo Grain Exchange. Review of Financial Studies 20, 1183–1218.

Easley, D., Kiefer, N., O'Hara, M., Paperman, J., 1996. Liquidity, information, and infrequently traded stocks. Journal of Finance 51, 1405–1436.

Ederington, L., Lee, J., 1995. The short-run dynamics of the price adjustment to new information. Journal of Financial and Quantitative Analysis 30, 117–134.

Foster, F., Viswanathan, S., 1990. A theory of interday variations in volumes, variances, and trading costs in security markets. Review of Financial Studies 3, 593–624.

Foster, F.D., Viswanathan, S., 1993. Variations in trading volume, return volatility, and trading costs: evidence on recent price formation models. Journal of Finance 48, 187–211.

Hasbrouck, J., 1991. Measuring the information content of stock trades. Journal of Finance 46, 179–207.

Holden, C., Subrahmanyam, A., 1992. Long-lived private information and imperfect competition. Journal of Finance 47, 247–270.

Kabir, R., Vermaelen, T., 1996. Insider trading restrictions and the stock market: evidence from the Amsterdam stock, exchange. European Economic Review 40, 1591–1603.

Lehmann, B., 2002. Some desiderata for the measurement of price discovery across markets. Journal of Financial Markets 5, 259–276.

Madhavan, A., Richardson, M., Roomans, M., 1997. Why do security prices change? A transaction-level analysis of NYSE stocks. Review of Financial Studies 10, 1035–1064.

Subrahmanyam, A., 1991. Risk Aversion, Market Liquidity, and Price Efficiency. Review of Financial Studies 4, 417–441.

Theobald, M., Yallu, P., 2004. Determining security speed of adjustment coefficients. Journal of Financial Markets 7, 75–96.

Vives, X., 1995. The speed of information revelation in a financial market mechanism. Journal of Economic Theory 67, 178–204.

Walras, L., 1874. Eléments d'Économie Politique Pure (L. Cobaz, Lausanne); Translated by William Jaffé, 1954, Elements of Pure Economics (Allen and Urwin, London).

Webb, R., 1995. Futures trading in less 'noisy' markets. Japan and the World Economy 7, 155–173.