The Matching Market Institution: A Laboratory Investigation

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The matching market (MM) trading institution matches the buyer with the highest bid to the willing seller with the highest ask, the second highest bidder to the second highest remaining willing seller, etc., until no seller remains who is willing to transact at any remaining buyer's bid. We will see in Section I that the MM institution maximizes trading volume for any given set of bids and asks, often generating about twice the trading volume of the standard uniform price trading institution.

The MM institution is of obvious interest to anyone who wishes to maximize trading volume (for example, brokers on commission). The Australian Stock Exchange uses a form of the MM to open each trading session.[1] Our interest in the MM, however, arose from its use by China's environmental protection agency (EPA).[2] The Chinese altered a different trading institution then used by the U.S. EPA that gives priority to the lowest, not the highest, remaining ask. In both countries, the buyer's bid defines the price in each transaction, apparently with the intention to shift surplus to the sellers.[3] The Chinese variant, the MM, may be intended to increase trading volume. Emissions permit trades in China usually involve an offset ratio greater than 1.0 (i.e., the seller eliminates more than 1 ton of emissions for each 1-ton permit acquired by a buyer), so increasing trading volume would help the EPA meet its goal of reducing total emissions.

But is the MM institution effective? Perhaps it achieves higher trading volume but sacrifices efficiency. Or perhaps traders react strategically to the MM incentives so as to maintain efficiency but thereby reduce the trading volume and the transfer of surplus. Evaluating such conjectures requires theoretical analysis and empirical evidence that is not available in existing literature.

Literature does exist for related market institutions. Cason (1995) and Cason and Plott (1996), among others, identified theoretically perverse incentives in the U.S. EPA institution and confirmed its inefficiency in laboratory experiments. Perhaps in response, the U.S. EPA has proposed changing to a uniform price auction (*Federal Register,* 1996). Extensive literature documents that uniform price institution is highly efficient in theory (e.g., Mark Satterthwaite and Steven Williams, 1993) and in the laboratory (e.g., Cason and Friedman, 1997).

The purpose of this paper is to report a first set of laboratory experiments comparing the

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[1] The National Association of Securities Dealers (NASD) recently proposed a version of MM to open trading sessions as part of a reform effort for the U.S. over-the-counter stock market. A 1997 version of the NASD proposal can be found at http://www.sec.gov/rules/proposed/naqcess.txt. We are grateful to Joel Hasbrouck for telling us about the use (current and proposed) of the MM to open stock trading sessions. Benny Moldovanu reminds us that some authors use the term MM more broadly than we do to refer to a wide class of mechanisms that includes the marriage market (David Gale and Lloyd Shapley, 1962).

[2] As explained more fully in Rich (1996), in 1992 the Chinese EPA introduced a pilot trading program for SO_2 emission permits in six cities. Trades are subject to administrative discretion but generally conform to the MM procedure.

[3] The U.S. EPA's motives are documented in Timothy Cason and Charles Plott (1996). In China, asks come predominantly from state-owned enterprises and entities that the EPA may wish to support. Dhananjay Gode (personal communication, January 6, 1997) tells us that local governments in India also use MM-like procedures with similar motives to shift surplus and maximize volume.

MM institution to the natural alternative, the uniform price (UP) or call market. In this paper, we focus on the MM's general properties; a companion paper (Rich, 1996) focuses on its role in emissions permit trading. Our experiments vary the trading institutions and several other treatment variables including the subject pool (half the sessions we conducted in China and half in the United States), the presence or absence of large demand shocks, and the degree of subject experience. The main performance variables are market efficiency, price, trading volume, and value revelation. We find that the subject pool and the demand shocks have little impact on the institutional comparison. Compared to uniform pricing, the matching institution results in lower efficiency, more variable trading volume, and less value revelation. We argue informally that Bayesian Nash equilibrium (BNE) theory and learning theory should be able to account for most of these regularities.

I. Relevant Theory

Our experiments compare market institutions in a very simple environment. Each buyer $i = 1, \ldots, n$ has an induced value or willingness to pay $v_i \geq 0$ for a single unit, and each seller $j = 1, \ldots, m$ has an induced cost $c_j \geq 0$ for a single unit. Table 1 shows typical induced values and costs for $n = 4$ buyers and $m = 4$ sellers. If buyer i transacts with seller j at price p, then the surplus $v_i - c_j$ is split between buyer i's profit $v_i - p$ and seller j's profit $p - c_j$. For example, if buyer 1 purchases from seller 2 at price 42, then the surplus $55 - 38 = 17$ is split with the buyer getting $55 - 42 = 13$ and the seller getting $42 - 38 = 4$.

Market performance has several dimensions. The most important measure is efficiency, the percentage of potential surplus that is actually realized. Efficiency depends in part on trading volume (the number of transactions) and on price, and these performance measures are of interest in their own right.

We compare performance across two market institutions. The uniform price institution is well known under various names, including call market, clearinghouse, and sealed bid-offer market. In UP, each buyer i submits a single bid b_i and each seller j simultaneously submits an ask a_j. The UP algorithm computes revealed supply $s(p) = \#\{j: a_j \leq p\}$ and revealed demand $d(p) = \#\{i: b_i \geq p\}$. It then sets price $p^{UP} = \inf\{p: s(p) > d(p)\}$ at which supply equals demand.[4] The algorithm rejects all bids below p^{UP}, all asks above p^{UP}, and if necessary, a minimal number of orders placed precisely at p^{UP}. All other orders, Q^{UP} bids and the same number of asks, are filled at the uniform price p^{UP}. In short, the UP institution clears the supply revealed by the asks against the demand revealed by the bids.

TABLE 1—AN EXAMPLE OF INDUCED VALUES AND COSTS FOR FOUR BUYERS AND FOUR SELLERS

Trader number	Buyer value	Seller cost
1	55	54
2	45	38
3	36	22
4	26	16

The other institution, matching market, is less well known but equally straightforward. Bids and asks are entered simultaneously as in the UP institution. The MM algorithm matches the highest bid $b(1) = \max\{b_1, \ldots, b_n\}$ with the highest ask not exceeding the bid, $a(1) = \max\{a_j: a_j \leq b(1)\}$, at price $b(1)$; matches the second highest bid $b(2)$ with the highest remaining ask not exceeding it, $a(2) = \max\{a_j: a_j \leq b(2)$ and j not yet matched$\}$, at price $b(2)$; and so on, until there remain no asks below any remaining bid.

A. *Marshallian Predictions*

An analysis of the UP institution is well known to beginning economics students at least since Alfred Marshall (1890). The Marshallian assumption, usually implicit, is that revealed supply and demand are the same as true supply and demand. Then p^{UP} is a competitive equilibrium price, Q^{UP} is a competitive

[4] Note that sometimes there is a range of prices at which supply equals demand, in which case we use the upper endpoint. This is to maintain as close comparability as possible to the other market institution, MM.

equilibrium quantity, and total surplus is maximized. For the economy in Table 1, the Marshallian predicted price is 38 and trading volume is 2, with buyers 1 and 2 transacting with sellers 3 and 4 and generating total surplus 55 + 45 − 22 − 16 = 62, or 100-percent efficiency.

The same Marshallian assumption leads to quite different conclusions with the MM institution. Transaction prices range from $p_L = \min\{v_i\colon v_i \geq v(m^*)$ and $v_i \geq \min c_j\}$[5] to $p_U = \max\{v_i\}$ and the trading volume is the (lesser of) total supply or total demand over this range, $Q^{MM} = \min\{S(p_U), D(p_L)\}$. (See Figure 1.) Note that volume is *maximized* subject to a participation or no-loss constraint, but in each transaction surplus is *minimized* at the highest bid subject to the no-loss constraint. For the economy in Table 1, the Marshallian predicted prices range from 26 to 55, volume is 4 with all traders participating, and total surplus is (55 − 54) + (45 − 38) + (36 − 22) + (26 − 16) = 32, or 32/62 = 51.6-percent efficiency.

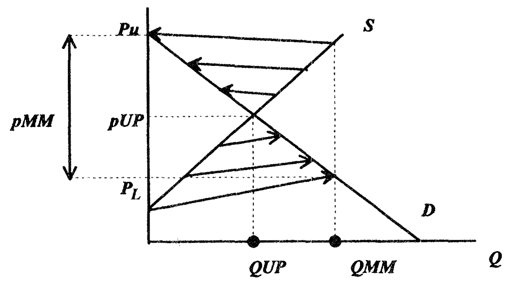

FIGURE 1. MARSHALLIAN ANALYSIS OF THE MM INSTITUTION

B. *Bayesian Nash Equilibrium Predictions*

Satterthwaite and Williams (1993) summarize a series of articles that predict behavior in the UP institution when traders exploit their ability to underreveal supply and demand. Assuming that buyers' values and sellers' costs are private information and drawn independently from known distributions, the literature obtains symmetric bid functions $b_i = B(v_i)$ and ask functions $a_j = A(c_j)$ that constitute a Bayesian Nash equilibrium. It turns out that, given our conventions noted in footnote 4, A is the identity function and B has slope less than 1.0. In other words, in strategic equilibrium the revealed supply is the true supply but the revealed demand is lower than the actual demand. (See Figure 2.) Thus the BNE prediction is that price, volume, and efficiency all are lower than in the Marshallian forecast of competitive equilibrium (CE).

The gap between the BNE and the Marshallian predictions depends on the postulated distributions of values and costs and on the actual values and costs. For example, if bids and asks are both independently and identically distributed random draws from the same uniform distribution on [0, M], where $M > 55$, then $B(x) = 0.8x$ and $A(x) = x$ (Williams, 1990). Using these functions and the Table 1 values and costs, we find that $p^{BNE} = 36 < 38 = p^{CE}$, but $Q^{BNE} = 2 = Q^{CE}$ and efficiency remains at 100 percent. If seller 3's actual cost were 37 instead of 22, however, the predicted Q would be 1 and efficiency would be much lower.

No BNE have yet been computed for the MM institution, but general considerations allow us to make some qualitative predictions. In the MM as in the UP institution, bids above true value and asks below true cost are dominated because they never lead to the expectation of a more favorable transaction than does full revelation.[6] Hence each buyer optimally reduces her bid below value (and each seller increases his ask above cost) to the point that: (1) the marginal loss from the reduced probability of transacting just equals (2) the marginal gain conditional on transacting.[7] For

[5] Here $m^* = \min\{n, m\}$; the constraint is that the lowest MM price p_L must be at least the value of the m-th buyer if there are fewer sellers (m) than buyers (n).

[6] By contrast, Cason (1995) shows in the U.S. EPA market institution that asks below cost can occur in strategic equilibrium.

[7] Indeed, in UP sellers have a dominant strategy to fully reveal because effect (2) is absent for them: the price is always set by a buyer or a nontransacting seller. See Cason and Friedman (1997) for more details and citations.

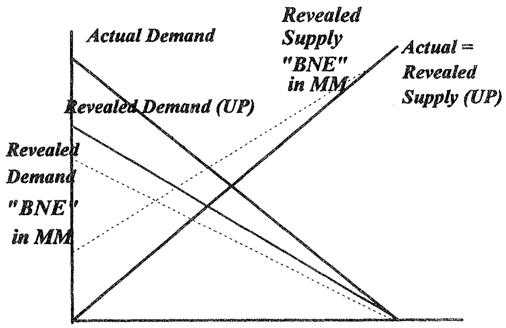

FIGURE 2. DEMAND AND SUPPLY FOR BNE IN UP AND MM

buyers, effect (2) is stronger and effect (1) is weaker in the MM than in the UP institution, because in each MM transaction the price is the buyer's bid, and bids below the UP marginal ask can still be filled in the MM institution. For sellers, effect (2) is again stronger and effect (1) is weaker in the MM than in the UP institution, because higher asks are more likely to be matched with higher bids, and there is a noisier relationship between ask price and rejection probability in MM than in UP. Thus both buyers and sellers should underreveal to a greater extent in MM than in UP. (Again, see Figure 2.)

Efficiency will be no greater in MM than in UP because revelation is less and because the matching algorithm is less efficient for given revealed supply and demand. The volume implied by the revealed supply and demand curves also is lower, but the MM algorithm squeezes more transactions out of given revealed supply and demand so the net result is unclear. Definitive volume predictions (and verification of the efficiency conjecture) await actual computation of Bayesian Nash equilibrium for the MM institution. Nevertheless, for brevity we will refer to the MM predictions of this subsection as "BNE."

C. *As-if Complete Information Nash Equilibrium Predictions and Learning*

Experimentalists at least since Lawrence E. Fouraker and Sidney Siegel (1963) have observed that complete information (as opposed to Bayesian) Nash equilibrium predictions often are quite accurate even when (or, as Vernon L. Smith et al [1991] argue, especially when) subjects' value and cost information is private. Friedman and Joseph Ostroy (1995) find that outcomes in their experiments using a version of UP and other market institutions are predicted better by NE ("as-if complete information NE") than by BNE. Citing previous theoretical work, they show that (as long as there are at least two transactions in competitive equilibrium) every NE for the UP institution is either trivial (no trade) or produces precisely a competitive equilibrium outcome.

The underlying idea is quite intuitive and extends directly to the MM institution. Suppose all other active traders bid and ask at a competitive equilibrium price. Then any given trader in the UP or in the MM who can profitably transact at the CE price can do no better than to bid or ask precisely at that price. Thus it is a NE for all marginal and intermarginal traders (those who transact in CE) to bid and ask precisely at CE and for extramarginal traders to fully reveal. The outcome then is CE price and quantity and 100-percent efficiency.[8]

How might a Nash equilibrium become established in which all relevant traders bid and ask a competitive equilibrium price? Friedman and Ostroy (1995) argue informally that it is the result of some adaptive learning process. Traders who underreveal more aggressively than in CE tend to miss profitable trades and traders who reveal more fully tend to transact at less favorable prices. Over time, then, traders in a stationary environment may converge to NE behavior even though they do not actually know other traders' values and costs.

Adaptive learning is imperfect even in the UP institution (Cason and Friedman, 1997) and it obviously works less quickly and reliably in the MM institution. For example, as

[8] The UP institution allows a broader range of NE that support CE outcomes; other traders need only bid or ask at CE at the relevant margin. The MM institution conceivably may have other nontrivial NE that do not support the CE outcome. In any case, it is clear that the MM institution does have NE that support the CE outcome, and our "as-if complete information NE predictions" (or NE predictions, for short) refer to those NE.

TABLE 2—SUMMARY OF THEORETICAL PREDICTIONS

	Marshallian	BNE	As-if NE	Adaptive learning
Efficiency:				
UP	100 percent	High	100 percent	High
MM	Lowest	Medium	100 percent	Medium
Price:				
UP	CE	< CE	CE	σ: *medium*
MM	$[P_L, P_U]$	μ < CE	CE	σ: *high*
Volume:				
UP	CE	< CE	CE	σ: *medium*
MM	> CE	?	CE	σ: *high*
Underrevelation:				
UP	None	Sellers: none Buyers: some	High for intermarginal traders	→ NE *rapidly*
MM	None	Sellers: more Buyers: more	High for intermarginal traders	→ NE *slowly*

Notes: UP refers to the uniform price market institution and MM to the matching market institution. CE refers to the competitive equilibrium benchmark. NE refers to Nash equilibrium and μ refers to the mean of empirical distribution and σ to the variance.

long as even one intermarginal buyer bids not far below true value, a seller with cost a bit below the CE price might be richly rewarded in the MM for asking well above cost. One should anticipate noisy feedback in the MM and consequently slow convergence and erratic trading volume during the learning process.

D. *Summary*

The matching institution is theoretically interesting because several a priori reasonable economic theories offer conflicting predictions of its performance. The Marshallian theory predicts high trading volume and low efficiency in MM relative to the competitive equilibrium volume and 100-percent efficiency predicted in the uniform price institution. The Bayesian Nash equilibrium theory predicts lower efficiency in the MM than in UP, while its predictions for price, volume, and efficiency in UP are all below CE. As-if NE predicts that both institutions will eventually implement CE in a stationary environment, but the underlying adaptive learning process predicts slower convergence in MM and more erratic price and volume. These theoretical predictions are summarized in Table 2.

II. Experimental Design

Our experiments compare the two different market institutions while controlling for the subject pool, the subjects' experience level, and the demand and supply. As shown in Figures 3A and B, the induced values and costs define ordinary downward-sloping demand and upward-sloping supply curves. The conversion factor makes the average hourly earnings slightly higher than average hourly local wages, about $10 per hour at the

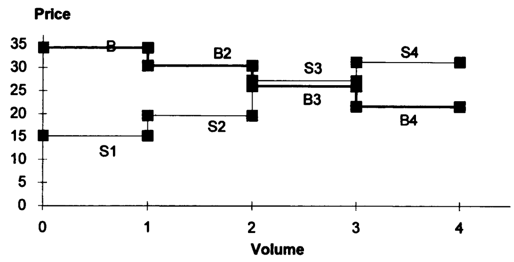

FIGURE 3A. INDUCED VALUES AND COSTS
INEXPERIENCED SESSIONS

Notes: In sessions with inexperienced subjects, supply is induced each period using cost schedule S1–S4. Demand is induced each period using value schedule B1–B4, producing the competitive equilibrium (CE) price = 27.2, the CE volume = 2, and the total CE profit = 30 each period. Parameter set C is essentially a 1:6.7 rescaling of set A.

University of California-Santa Cruz (UCSC) and about 25 yuan per hour at Wuhan University, China. We report the results of 10 sessions, 5 at each site, each with 20 to 40 trading periods. The UCSC sessions were computerized, while the Wuhan sessions were conducted by hand.[9]

During sessions conducted by hand, the experimenter collects all bids and asks at the end of each trading period and writes them on the blackboard. Bids are arrayed from highest to the lowest; asks from lowest to the highest in UP. Clearing price always is the fourth highest bid or ask in UP. (This is due to the total supply of four units and the convention of using the highest clearing price.) In computerized sessions, each period the computer collects the bids, computes the outcomes, and reports them on each subject's screen.

In the matching market, bids and asks are collected and displayed. Asks as well as bids are arrayed from highest to the lowest. The buyer with the highest bid is matched with the seller who has the highest ask that is below the highest bid, and then the buyer with the second highest bid is matched with the remaining seller with the highest ask that is below the second highest bid, and so on. For example, the board or screen might show the following bids, asks, and matches:

Bids	Asks
4.60	6.00
3.75	4.00
2.25	2.81
1.50	1.40

The buyers pay their bid prices, e.g., 4.60, 3.75, and 2.25 in the example above, while the ask for 6.00 and the bid for 1.50 are rejected.

The subjects are recruited from the Department of Business Administration sophomore class and Law School at Wuhan University, China, and undergraduate economics classes at UCSC. At the beginning of each experiment session, subjects are permanently assigned as either buyer or seller by random drawing. In order to avoid complaints of unequal trading opportunity, assignments to buyers' values are rotated every eight periods, and seller assignments are also rotated at the same time.

Table 3 summarizes the overall design and treatments. For the inexperienced sessions 1–3 and 6–8, we have four buyers and four sell-

[9] Two pilot sessions, one by hand and one by computer, were also conducted at UCSC. We omit them from our data analysis because they were relatively short and used slightly different conventions.

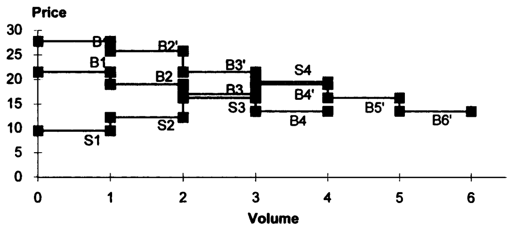

FIGURE 3B. INDUCED VALUES AND COSTS EXPERIENCED SESSIONS

Notes: In sessions with experienced subjects, supply is induced each period using cost schedule S1–S4. Demand is induced in some periods using value schedule B1–B4, producing CE price = 17.0, CE volume = 2, and CE total profit = 18.75. In other periods demand is induced using B1′–B6′, producing CE price = 19.5, CE volume = 3, and CE total profit = 36.25. Parameter sets D and D′ are 1:7.1 of rescaling of sets B and B′.

ers. We add on two additional buyers in the parameter set during experienced sessions 4 and 5, and 9 and 10 to observe the effects of a demand shock as shown in Figure 3B.[10] We vary the market institution in a balanced manner within each session and across sessions in order to reduce the problem of confounding time or learning with the key treatment variable. Our within-group design is conservative for assessing the impact of market institution and demand shock (Friedman and Shyam Sunder, 1994). On the other hand, the impacts of the subject pool and of subjects' experience level may be overstated due to the across-group design for these variables.[11]

III. Results

We begin with a descriptive overview of the experimental results. Then we present hypothesis tests results on four treatment variables: market institutions, subject pool, experience level, and demand shock.

[10] The shocks put our environment somewhere between the usual stationary repetition featured in most laboratory markets and the random values of Cason and Friedman (1997) and a few other studies. As explained in Rich (1996), the shocks were motivated mainly by policy considerations but also have some potential value for theory testing.

[11] For more details of experimental procedure, please see Rich (1996). The instructions to the subjects are available from Rich on request.

1. *Overview.*—Table 4 presents descriptive statistics for several measures of performance. There are 264 market periods in 10 sessions. The number of observations for some price variables is 262 due to zero transactions in 2 periods. Recall that efficiency is defined as the observed total profits in a period as a fraction of the maximum possible profits (i.e., trading profit/CE profit). The overall mean efficiency is 86 percent, but only 80 percent under the matching market compared to 92 percent under the uniform price market.

Price deviation or PDV (and volume deviation or VDV) are defined each period as the observed trading price[12] (and observed volume) minus competitive equilibrium price (volume) and then divided by CE price (volume). The absolute values of PDV are denoted PDVAB (and VDVAB). These variables are in percentage terms, which allows us to compare the performances of transaction prices and volumes under different parameter sets. Note that prices in both market institutions average about 2 percent below CE, and that average volume is also slightly below CE in both institutions. The accuracy of CE may be overstated here because negative and positive deviations may cancel each other out. Indeed, average absolute price deviation is 5 percent

[12] The observed price in a given MM period is the mean transaction price that period. Of course, in UP there is only a single transaction price each period.

TABLE 3—EXPERIMENTAL DESIGN AND TREATMENTS

Session	Date	Number of players	Subject experience	Mode	Location	Parameter set	Market institution	Periods
1	9/5/95	8	Inexperienced	By hand	Wuhan	A	Matching Uniform	3–6, 17–20 9–16
2	9/6/95	8	Inexperienced	By hand	Wuhan	A	Matching Uniform	3–6, 17–20 9–16
3	9/7/95	8	Inexperienced	By hand	Wuhan	A	Matching Uniform	3–6, 17–20 9–16
4	9/7/95	10	Experienced	By hand	Wuhan	B & B′	Matching Uniform	2–5, 15–22 7–14
5	9/8/95	10	Experienced	By hand	Wuhan	B & B′	Matching Uniform	7–14 2–5, 15–22
6	11/1/95	8	Inexperienced	Computer	UCSC	C	Matching Uniform	1–4, 13–16, 21–28 5–12, 17–20, 29–32
7	11/2/95	8	Inexperienced	Computer	UCSC	C	Matching Uniform	1–4, 13–16, 21–28 5–12, 17–20, 29–32
8	11/8/95	8	Inexperienced	Computer	UCSC	C	Matching Uniform	1–4, 13–16, 21–28 5–12, 17–20, 29–32
9	11/14/95	10	Experienced	Computer	UCSC	D & D′	Matching Uniform	1–4, 13–20, 25–32, 37–40 5–12, 21–24, 33–36
10	11/15/95	10	Experienced	Computer	UCSC	D & D′	Matching Uniform	5–12, 21–24, 33–36, 1 2–4, 13–20, 25–32, 37–40

in MM compared to 3 percent in UP, and average absolute volume deviation is 21 percent in MM and 5 percent in UP.

The last entries in the table adapt the Cason and Friedman (1997) measurements for the degree of underrevelation. Buyer underrevelation (BUR) is defined for each buyer each period as (value − bid)/value. Similarly, seller underrevelation (SUR) is defined as (ask − cost)/cost. These ratios represent the fraction of value discounted in a bid, and the cost "markup" relative to the true cost. The mean is a poor indicator of central tendency for the ratios because of a substantial number of outliers, especially in SUR due to small denominators. Hence we focus on the median as the measure of central tendency. The median values of both BUR and SUR are larger in MM than in UP, which indicates greater underrevelation under MM. The median values for BUR exceed their SUR counterparts, again as expected.

2. *Hypothesis Tests for Market Institutions.*—Table 5 presents the treatment effects (and p-values) for the main treatments. The first column of Table 5 lists seven dependent variables of interest. The top row lists four dummy variables for the key treatments: market institutions (MMUP = matching versus uniform price), subject pool (WUUC = Wuhan versus UCSC), subjects' experience levels (ELEVEL), and demand shocks (SHOCK = six buyers versus four). The table entries are differences between means of treatment variables. The parenthetical p-values are for the t-test of the null hypothesis that the treatment has no effect. The entry −0.121 for MMUP efficiency, for example, indicates that efficiency is 12.1 percent lower in MM than in UP, and the null hypothesis of no difference is being rejected at the confidence level of 0.0001, in favor of the alternative that UP markets are more efficient than MM.

TABLE 4—DESCRIPTIVE STATISTICS

Variable	N	Mean	Median	Standard deviation
Efficiency overall	264	0.856	1	0.221
Matching market (MM)	133	0.796	0.910	0.248
Uniform price market (UP)	131	0.917	1	0.170
Transaction price deviation (PDV) overall	262	−0.020	−0.020	0.053
Matching market	131	−0.021	−0.02	0.062
Uniform price market	131	−0.019	−0.012	0.042
Absolute value of PDV (PDVAB) overall	262	0.042	0.033	0.037
Matching market	131	0.052	0.044	0.039
Uniform price market	131	0.033	0.019	0.033
Trading volume deviation (VDV) overall	264	−0.028	0	0.256
Matching market	133	−0.006	0	0.330
Uniform price market	131	−0.050	0	0.146
Absolute value of VDV (VDVAB) overall	264	0.131	0	0.222
Matching market	133	0.212	0	0.253
Uniform price market	131	0.050	0	0.146
Buyer underrevelation ratio (BUR) overall	1,264	0.1239	0.0930	0.1328
Matching market	637	0.1367	0.1204	0.1209
Uniform price market	627	0.1108	0.0698	0.1428
Seller underrevelation ratio (SUR) overall	1,045	0.1917	0.0294	0.2999
Matching market	526	0.2227	0.0526	0.3025
Uniform price market	519	0.1603	0.0172	0.2942

Notes: Efficiency = trading profit/CE profit; PDV = (transaction price − CE price)/CE price; VDV = (trading volume − CE volume)/CE volume; BUR = (value − bid)/value; and SUR = (ask − cost)/cost.

The entries in the first column of Table 5 and the data in Table 4 allow us to evaluate two theoretical predictions of Table 2. Median UP efficiency is 100 percent but the mean is noticeably lower, consistent with the Bayesian Nash equilibrium and adaptive learning (AL) theories. MM efficiency is significantly lower than UP efficiency, consistent with all theories other than (asymptotic, as-if) NE.

Mean price tends to lie very slightly below the CE level (roughly consistent with all theories) with no significant difference in mean deviation between the two institutions (contrary to BNE). Absolute deviation is significantly larger in the MM institution, consistent with AL.

Mean volume also tends to lie a bit below the CE level with no significant difference between the institutions (contrary to Marshall).

TABLE 5—TREATMENT EFFECTS (AND p-VALUES)

Variables	MMUP	WUUC	ELEVEL	SHOCK
Efficiency	−0.121 (0.0001)	0.084 (0.0016)	0.009 (0.41)	0.034 (0.11)
Price deviation (PDV)	−0.002 (0.25)	−0.013 (0.06)	0.008 (0.26)	0.006 (0.79)
Absolute value of PDV (PDVAB)	0.019 (0.0001)	0.006 (0.24)	0.000 (0.42)	−0.005 (0.23)
Volume deviation (VDV)	0.044 (0.60)	0.081 (0.01)	−0.038 (0.09)	−0.006 (0.25)
Absolute value of VDV (VDVAB)	0.162 (0.0001)	−0.009 (0.63)	−0.009 (0.52)	−0.035 (0.18)
Buyer underrevaluation ratio (BUR)	0.026 (0.0001)	−0.007 (0.643)	0.036 (0.022)	0.035 (0.098)
Seller underrevelation ratio (SUR)	0.062 (0.0001)	−0.063 (0.001)	0.085 (0.0002)	0.060 (0.581)

Notes: Treatment effects are the difference of means between the two treatment variables. p-values are in parentheses. For example, the first entry −0.121 for efficiency under MMUP indicates that mean efficiency under MM is 12.1 percent lower than mean efficiency under UP. The other treatment effects are WUUC = Wuhan University subject pool mean minus UCSC mean, ELEVEL = inexperienced or experienced subjects, and SHOCK = parameter set A & B, and C & D mean minus parameter set B′ and D′ mean.

Volume absolute deviations from CE are significantly less in UP, consistent with AL.

Median underrevelation by sellers was less than 2 percent in UP (roughly consistent with BNE), but mean underrevelation was quite high at 16 percent, consistent with AL. Buyer underrevelation in both institutions and seller underrevelation in MM were all quite substantial, contrary to Marshall. Median underrevelation seems to be greater for buyers than for sellers in both institutions, consistent with BNE. Also consistent with BNE (and, for different reasons, with AL), underrevelation by both buyers and sellers was much more extensive in the MM then in the UP institution.

3. *Other Hypothesis Tests.*—The impact of subject pool unfortunately is confounded by the market implementation. All sessions were conducted by hand in China while computers were used at UCSC. Efficiency is higher in Wuhan than in UCSC (91 percent > 83 percent). Anova test results (Table 5) confirm the mean efficiency under different locations (WUUC) are significantly different (p-value 0.0016). Table 5 also indicates possibly significant impact of WUUC on price and volume levels PDV and VDV, but generally not on absolute deviations PDVAB and VDVAB. See Rich (1996) for a more detailed analysis that uses nonparametric tests to confirm the main conclusions, and that analyzes interactions of the treatment variables.

We offer two interpretive comments. First, the impact of WUUC probably arises mainly from the difference between computerized and by-hand sessions. Such differences were observed during the pilot experiments at UCSC (one session by hand and one session by computer) and are documented in other market institutions such as the continuous double auction (Friedman and Sunder, 1994). Markets conducted by hand seem to encourage faster learning and more intense competition. Second, our primary conclusions about market institutions are valid for each subject pool separately. For example, in the Wuhan sessions separately, efficiency is lower, transaction prices are lower, and trading volumes are more variable under the matching institution.

The primary conclusions therefore seem robust to both subject pool and to implementation, computerized, or by hand.

The final performance measure we consider is the surplus split. Define ratio of sellers' profit (RSP) as actual profits earned by all sellers in a given market period as a percentage of profits that sellers would earn in competitive equilibrium. Likewise, define RBP as the ratio of buyers' actual profit to CE profit. Overall, average RBP is 91.2 percent in MM versus 99.9 percent in UP, while average RSP is 72.9 percent in MM versus 86.6 percent in UP. Thus the profits of both buyers and sellers are notably lower in MM than in UP. To assess the relative loss (or surplus split per se) we consider the ratio of average RSP to average RBP. The ratio is 79.9 percent in MM and 86.7 percent in UP. Thus the MM impairs sellers' relative as well as absolute profitability.

IV. Discussion

Our laboratory comparison of the matching market and uniform price institutions has two main motivations. First, because of its intuitive appeal, simplicity and contemplated use in important field markets, the MM institution is intrinsically interesting and so its performance characteristics are worth investigating. Second, several general theories of price formation have contrasting predictions for the two market institutions and so the empirical comparison should help refine theory.

Our findings offer little encouragement to advocates of the MM in field markets. The MM institution fails to generate consistently higher trading volume, its main selling point. A secondary selling point is that the MM would offer sellers a larger share of the surplus and we document its empirical failure in this respect as well. In our experiments, the mean volume was essentially the same as in UP, but more variable in the MM. Prices were also more variable in MM, even after averaging across transactions within a period. The main problem with the MM in practice is that it is much less efficient: loss of potential gains from trade averaged about 8 percent in UP and about 20 percent in MM.

Our findings should help refine theories of price formation. The simple textbook or Marshallian theory slightly overpredicts price and grossly overpredicts volume in the MM institution. The reason is that buyers substantially understate their willingness to pay and sellers understate their willingness to accept in both institutions but especially in the MM institution. Our findings are generally consistent with two different alternative theories, the now-orthodox game-theoretic approach of Bayesian Nash equilibrium, and an adaptive learning theory. BNE predicts the underrevelation of willingness to pay/accept, but such underrevelation is also consistent with AL. Likewise, AL predicts the greater fluctuations in transaction price and volume in MM, but such fluctuations may be consistent with BNE.

Much work remains, both theoretical and experimental.[13] Certainly BNE should be computed explicitly for the MM institutions, and AL models should be developed fully for both institutions. The possible impact of risk aversion should be considered. On the experimental side, it might be useful to examine different stationary configurations of demand and supply that have asymmetric division of surplus in competitive equilibrium or that have a unique competitive equilibrium price but nonunique quantity. Random values environments (as for example in Cason and Friedman, 1997) might also be useful in comparing the theoretical models, and more careful comparisons of behavior in by-hand versus computerized markets might provide further insight into the adjustment process. Even if the MM turns out to have little enduring practical value, it will remain a useful test case for theory.

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