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Financial market design and bounded rationality: An experiment ☆

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Abstract

This paper experimentally compares a Call Market and a Walrasian Tatonnement under asymmetric information. The experimental environment and the market institutions are such that, at the theoretical equilibria, the two trading institutions exhibit identical prices and surpluses. During the experiment, prices are fully revealing on the two trading venues. However, the gains from trade are higher on the Walrasian Tatonnement than on the Call Market. This is because uninformed agents trade less on the CM. I show that this behavior is due to bounded rationality and strategic uncertainty, and that the Walrasian Tatonnement fosters learning by mitigating the impact of both

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factors. This paper supports the view that trading institutions should be designed including cognitively ergonomic features to fit the limited nature of human rationality.

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0. Introduction

Asset pricing theorists often focus on equilibrium and not on equilibration, implicitly assuming that equilibrium is achieved instantaneously. There is however no disagreement that equilibration is a process and depends on market structure.[1] Analyzing such dependence involves out-of-equilibrium reasoning. The objective of this paper is to document the different out-of-equilibrium patterns induced by a Call Market and a Walrasian Tatonnement.

I use an experimental environment inspired by Plott and Sunder (1982) in which there is asymmetric information and explicit gains from trade. My methodological contribution is to design the experiment such that the two market institutions have the same Nash equilibrium outcomes: the prices and quantities traded at both fully and partially revealing equilibria are identical on both the Call Market and the Walrasian Tatonnement. This allows me to study the influence of market structure on the equilibration process in a context where it does not affect equilibrium outcomes.

During the initial replications of the experiment, the gains from trade extracted on both market institutions start at low out-of-equilibrium levels. On the Walrasian Tatonnement, these gains from trade increase in latter replications and converge towards fully revealing equilibrium levels while on the Call Market they do not. This difference is not due to the fact that traders coordinate on different equilibria: on both market institutions, prices in the experiment are fully revealing indicating that informed traders coordinate on a fully revealing equilibrium. For uninformed traders, the Walrasian Tatonnement appears more conducive to learning and equilibrium discovery than the Call Market.

My interpretations are that the Walrasian Tatonnement generates easier mental representations and partly isolates traders from strategic uncertainty. The mental representation interpretation is related to Camerer (1999): different extensive forms of a given game generate different mental representations and can induce different behaviors. In my experiment, traders on the Walrasian Tatonnement observe the operation of the law of demand and supply, whereas traders on the Call Market have to reason about the effect of this law. With perfectly rational agents, this distinction makes no difference and the two market institutions have the same equilibrium outcomes. With human traders, however, the easier mental representations generated by the Walrasian Tatonnement improve market performance.

According to the strategic uncertainty interpretation, traders may have an interest not to play equilibrium if other market participants deviate from their equilibrium

[1]For example, Plott and Smith (1978), and Plott and Sunder (1988) analyze the equilibration properties of various market institutions.

strategy.[2] Traders on the Walrasian Tatonnement observe the price before transacting. When implementing their equilibrium strategy, they can thus avoid trading at out-of-equilibrium prices. Such a protection against strategic uncertainty is not available on the Call Market where, to play a fully revealing equilibrium strategy, uninformed traders have to submit aggressive limit orders that expose them to trading at out-of-equilibrium prices. If they want to protect themselves from strategic uncertainty, uninformed traders on the Call Market have to deviate from fully revealing equilibrium strategies and submit conservative orders. I provide evidence which is consistent with these two interpretations.

Comparing the multi-stage Walrasian Tatonnement and the one-shot Call Market mechanisms might seem unfair and leading to an obvious result. However, this is only ex-post reasoning. Even if the price uncertainty in the Walrasian Tatonnement is resolved before trading, uninformed traders still have to learn to form rational expectations, i.e., they have to discover the correspondence between prices and the value of the asset.

The result that some market institutions are more conducive to learning than others has implications for the design of financial markets. Presumably, learning in the laboratory mirrors the fact that investors also learn in real markets. Thus, understanding what type of markets are conducive to learning is important. In particular, one purpose of market institutions may be to facilitate learning during transitions into new environments and after entrance of inexperienced traders. Once agents have learnt their new equilibrium behavior, for example via a Walrasian Tatonnement, then the market can switch to a faster institution such as a Call Market. The preopening and opening procedures in the Paris Bourse and the NYSE are examples of institutions that are close to the Walrasian Tatonnement.[3] A longer-lived need for an institutional arrangement such as the Walrasian Tatonnement arises in markets where there are frequent new traders' arrivals and fundamental parameter changes.

My experimental approach is in the spirit of Bossaerts and Plott (2004) in the sense that predictions on the behavior of financial markets are derived theoretically and tested using experimental data. While Bossaerts and Plott (2004) use a competitive equilibrium framework and focus on equilibration in double-auction markets, the present paper uses a game-theoretical analysis and investigates the impact of various market institutions on the discovery of equilibrium. My focus on game theoretical predictions is also a major difference with the seminal papers of Plott and Smith (1978) and Plott and Sunder (1988). This focus appears appropriate in light of the fact that the experimental markets considered here involve a fairly small number of agents. In addition, it allows me to identify the existence of bounded rationality and strategic uncertainty.

Several experiments have analyzed uniform-price market mechanisms. Two previous studies by Joyce (1984) and Bronfman et al. (1996) deal with the Walrasian Tatonnement. These papers use a private value environment and study the performance of this trading mechanism in achieving the competitive equilibrium. The Call Market has also been the

[2]Crawford (1997) defines another type of strategic uncertainty that emerges when there are problems of coordination among multiple equilibria. Section 2 presents evidence suggesting that coordination problems do not affect my experiment.

[3]Before the introduction of the OpenBook service in January 2002, market participants (except the specialist) could not observe the state of the order book. Before this date, NYSE's opening procedure was thus in the spirit of the Call Market. Madhavan and Panchapagesan (2000) study this procedure and the role of the specialist in a closed book setting. Baruch (2005) analyzes the impact of a change in transparency from a closed to an open order book.

object of experimental investigations in a private value framework. Cason and Friedman (1997) compare individual behavior to the Bayesian Nash Equilibrium bidding theoretical predictions. The present paper complements these articles in two respects. On the one hand, it offers a comparison of the two trading venues. On the other hand, it studies an environment with common values and asymmetric information that is more closely related to financial markets.

My findings echo the results of Kagel et al. (1987). They show that an English auction performs better than a second-price auction, thereby contradicting their risk-neutral bidding theoretical benchmark. They put forward the potential risk aversion of the subjects to explain the observed deviations from equilibrium. The results presented here cannot be interpreted in these terms since the theoretical analysis is independent from the degree of risk aversion.

In the rest of this paper, I refer to the Walrasian Tatonnement as WT and to the Call Market as CM. The next section describes the experimental design and the two market institutions under examination. Section 2 provides a game-theoretical benchmark. Section 3 compares the experimental performances of the two market institutions. Section 4 investigates the relative impact of bounded rationality and strategic uncertainty. The last section offers some concluding remarks.

1. Experimental market design

The experiment is run with 15 different cohorts of students from Toulouse University. Subjects are senior undergraduate students in business administration from the *Maîtrise de Science de Gestion* (M.S.G.). Each cohort includes 8 or 10 subjects.[4] A session consists of 10 replications of the experiment. Each cohort trades under a unique market structure, either a CM or a WT, for the whole session, and participates in only one session. Eight sessions were organized as a CM, seven as a WT. I have preferred a between-subject experimental design to a within-subject design in order to give participants the opportunity to learn equilibrium strategies while keeping constant the institutional environment. This choice isolates the experimental analysis from the issue of the transfer of learning across different types of games.[5] The instructions for the WT experimental sessions are presented in Appendix A. For the CM sessions, the instructions are similar except for the part related to the trading process. During the experimental sessions, no communication among agents is allowed. Each experimental session lasts approximately 2 hours.

1.1. Environment and incentives

1.1.1. Asset value and information

The environment is inspired by Plott and Sunder (1982). It has both private value and common value elements. Subjects can trade an asset whose common value V can be either

[4] One cohort under the CM (cohort 1030001) and one under the WT (cohort 1102001) included 10 subjects. All the other cohorts included 8 participants. The results presented in this paper are the same if the 10-player cohorts are excluded from the analysis.

[5] Potential cohort effects are overcome by the fact that (i) all the subjects come from the same pool of students namely M.S.G., and (ii) subjects have been randomly assigned to a particular cohort.

€2 or €8 with the same probability, one half.[6] This common value element is drawn at the beginning of each replication of the trading game but is not publicly announced. It is only revealed at the end of the replication after transactions have occurred.

In addition, a private value is publicly assigned to each subject: it is either $+1$ or -1. The private value of a subject remains the same for the entire experimental session. Overall, the asset value for a "+1" subject can be either €3 or €9; the asset value for a "–1" subject can be either €1 or €7. On the market, the number of "+1" subjects is equal to the number of "-1" subjects. The structure of the asset's value creates explicit gains from trade, under symmetric information about V, between "+1" subjects on the buying side of the market and "-1" subjects on the selling side.

Private information is introduced as follows. At the beginning of each replication and before the trading period starts, half of the "+1" subjects and half of the "-1" subjects receive a perfect signal indicating whether the common value V is €2 or €8. I refer to these subjects as informed traders or insiders. Every agent receives the signal five times per session.[7]

1.1.2. Endowments and asset portfolio

Subjects start each replication with a monetary endowment of €10 and no assets. Traders can buy or sell at most one unit of asset per replication. Short sales are allowed. At the end of each replication, subjects' final wealth is computed as the initial cash endowment plus the proceeds from sales minus the cost of purchases plus the value of the portfolio reflecting the common value V and the private component ($+1$ or -1). For instance, if a "-1" subject buys at a price equal to €6 one unit of asset whose common value is €8, her final wealth is: 10–6 + (8–1) = €11.

1.1.3. Incentives

Subjects receive explicit incentives. As in Selten, Mitzkewitz, and Uhlich (1997) and Biais, Hilton, Mazuriev, and Pouget (2005), their final wealth is converted into grade points.[8] Subjects are told verbally and in the written instructions that their grade for the finance course will reflect their final wealth. The grade for the course is between 0 and 20. Typical grades in the course range from 5 to 15 out of 20. The formula used to convert subjects' final wealth into bonus points is:

$$\left[\frac{\sum_{t=1}^{10} W_t - 98}{2}\right]^+,$$

where W_t represents the final wealth of the subject at the end of replication t.

This formula is publicly announced to the subjects. The bonus points earned during the experiment are added to subjects' final grade to determine the course grade. The

[6] Strictly speaking, subjects can trade digital options rather than asset shares since the traded claims exist in zero net supply.

[7] When there are 10 subjects per cohort, the number of "+1" and "-1" subjects is an odd number. In this case, the numbers of uninformed and informed agents are not identical. The distribution of signals and the private value component of each subject is available upon request.

[8] I have run four additional sessions with monetary incentives, two sessions under the CM regime and two under the WT regime. Providing subjects with monetary incentives does not alter the conclusions of the paper.

experiment is run during the course of the semester and thus before the final exam. During the experiment, the number of bonus points earned by the subjects averages 4, and ranges from 0 to 8.

1.2. Market institutions

1.2.1. Call Market

A CM is a uniform-price order-driven market in which traders submit limit orders. These orders are aggregated to determine the market clearing price. The experimental CM includes the next four steps.

Step 1: subjects privately submit at most one buy limit order and at most one sell limit order to exchange at most one unit of the asset. Subjects can choose any limit price they want between 0 and 10 with increments of 1.

Step 2: the central auctioneer aggregates the orders to build supply and demand curves.

Step 3: the market-clearing price is determined so as to minimize the absolute excess demand. If several prices satisfy this minimizing condition, the trading volume maximizing price is chosen. If more than one price still remains and if the sign of the excess demand does not change over these prices, the market clearing price is defined to be the highest (lowest) price if demand is greater (smaller) than supply. In the other cases, the market-clearing price is randomly determined within the set of prices satisfying all of the above conditions, each price in this set being equally likely. For a given market-clearing price, if a trader is on the buying and on the selling sides of the market, her orders cancel out.

Step 4: the market-clearing price is publicly announced. A multilateral transaction occurs. When at this price, demand and supply are not equal, the following rationing rule is applied: when the excess demand is equal to $X>0$ ($X<0$), X subjects are randomly selected among the buying (selling) agents and are excluded from the transaction.

The CM bears some similarities to a second-price auction since traders do not pay or receive what they bid or offer (i.e., their limit price) but rather a more advantageous market-clearing price. This feature and the CM rules are publicly announced at the beginning of each CM session. In the CM, traders cannot observe tentative prices. In addition, they do not have access to the order book before submitting their bids.

1.2.2. Walrasian tatonnement

A WT is a price-driven market mechanism whereby an auctioneer announces prices at which traders engage in transactions as soon as demand equals supply. The experimental WT includes the next four steps.

Step 1: the central auctioneer publicly announces a price that equals the expected common value of the asset, i.e., €5.

Step 2: subjects privately submit a one unit market order to buy or to sell at the announced price, P. If the aggregate demand (D) equals the aggregate supply (S), step 3 occurs; otherwise, the market proceeds to step 4.

Step 3: the tatonnement stops and a multilateral transaction occurs at the announced price P. Note that if $D=S=0$, subjects end up the replication with their initial wealth.

Step 4: a new price (P') is announced which is equal to: $P'=P+1$ if D-$S>0$, and $P'=P$-1 if D-$S<0$. The market then proceeds to step 2. However, note that the tenth announced price is necessarily a transaction price.[9] At this price, when demand and supply are not equal, the following rationing rule applies: when the excess demand is equal to $X>0$ ($X<0$), X subjects are randomly selected among the buying (selling) agents and are excluded from the transaction.

The price updating rule specified in this tatonnement process is in the spirit of a sequential auction. This updating rule and the entire WT rules are publicly explained at the beginning of each WT session. In the WT, traders may observe tentative prices before transactions occur but they cannot observe order imbalances.

2. Theoretical benchmark

In order to provide a basis to interpret the experimental results, I analyze theoretically the games described in the previous section. I assume that traders are perfectly rational in the sense that they maximize their expected utility, update their beliefs using Bayes rule, and have rational expectations. The analysis is in the spirit of Radner (1979) except that it deals with strategic agents. Appendix B formally states and proves the results discussed in this section.

Whatever the degree of risk aversion, the CM and the WT have identical theoretical properties: on both markets, there exist two equilibrium sets, a fully revealing set and a partially revealing set, associated with the same prices and allocations across market institutions. The fully revealing equilibrium set features perfectly revealing prices and full extraction of the gains from trade. The price is 1, 2, or 3 when V equals 2, and the price is 7, 8, or 9 when V equals 8. The total surplus equals the number of traders. Fig. 1 provides a graphical illustration of revealing equilibrium strategies. Panel A of Fig. 1 corresponds to the CM. "$+1$" insiders submit limit orders to buy at prices up to V, and to sell at prices above V. "-1" insiders submit limit orders to sell at prices up to V, and to buy at prices below V. "$+1$" uninformed traders submit limit orders to buy at prices up to 8 and to sell at prices up to 9. "-1" uninformed traders submit limit orders to buy at prices up to 1 and to sell at prices up to 2. Panel B of Fig. 1 corresponds to the WT. Insiders offer to buy when tentative prices are below V, and to sell when they are above. Uninformed traders do not submit any order as long as the price is not equal to one of the potential common values of the asset. When the price equals V, "$+1$" traders offer to buy while "-1" traders offer to sell.

The partially revealing equilibrium set features transactions in only one of the two states of nature: this set exhibits prices of 1, 2, or 3 when $V=2$, and no transaction when $V=8$, or prices of 7, 8, or 9 when $V=8$, and no transaction when $V=2$.[10] The expected gains from trade are lower than half the full extraction level. Fig. 2 provides a graphical example of a partially revealing equilibrium where the price is 2 when V equals 2, and where there is no transaction when V equals 8. Panel A of Fig. 2 corresponds to the CM. "$+1$" insiders always submit a limit order to buy at prices up to 2. "-1" insiders submit a limit order to sell at prices up to 2 when V equals 2, and a limit order to

[9] A limitation on the number of iterations is imposed to ensure that the process does not cycle indefinitely.

[10] Strictly speaking, this type of equilibrium is revealing in the sense that an outside observer could tell what the state of nature is after observing the market outcome: the presence or absence of transactions indicate the realized state of nature. However, if there were more than two states of nature, the equilibrium would only be partially revealing since the presence of transactions would indicate the realization of one of the two extreme states of nature but the absence of transactions would not allow the observer to disentangle the remaining states.

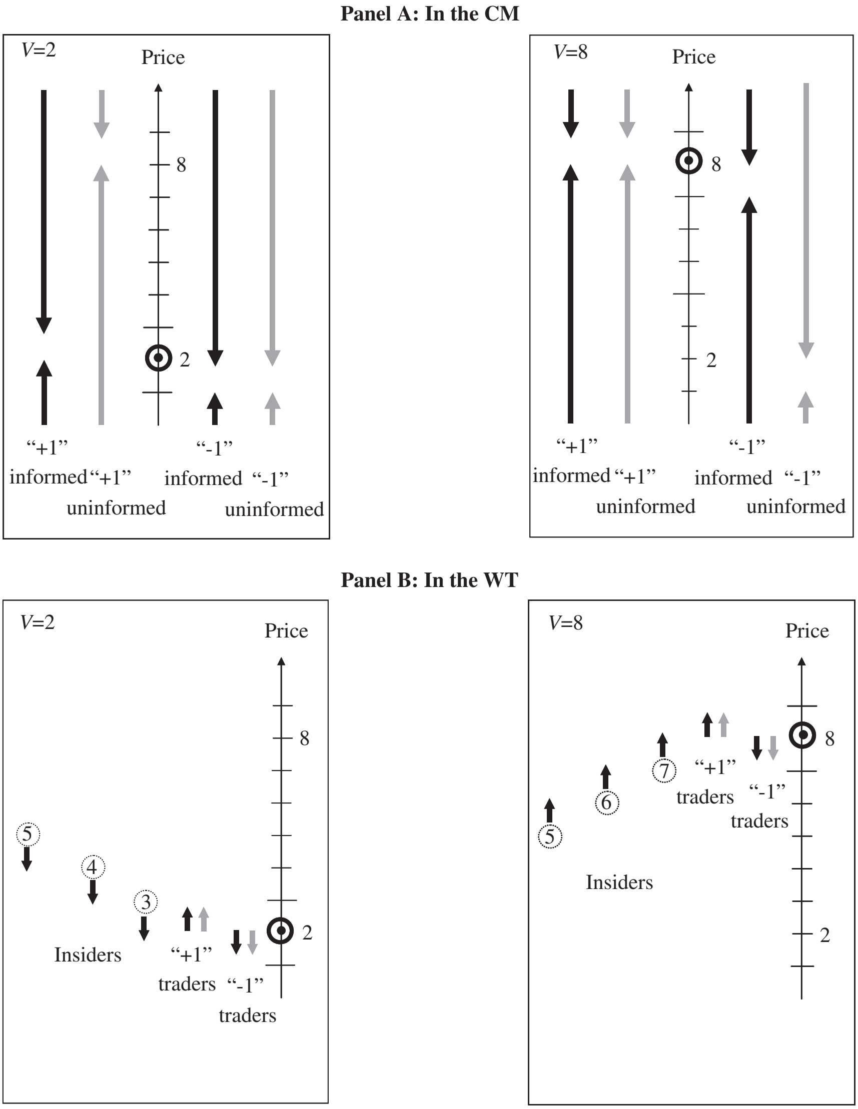

Fig. 1. Examples of fully revealing equilibrium strategies. Left boxes correspond to $V = 2$, right boxes to $V = 8$. Thick black circles indicate the transaction price. Dotted circles in the WT indicate the successive tentative prices. Arrows pointing to the top (bottom) represent buying (selling) limit orders. The black (grey) color refers to informed (uninformed) traders.

buy at prices up to 2 when V equals 8. "+1" uninformed traders submit a limit order to buy at prices up to 2. "−1" uninformed traders do not offer to trade. Panel B of Fig. 2 corresponds to the WT. "−1" insiders offer to sell as long as the tentative price is higher than 2; they sell if the tentative price is 2 when $V = 2$, and do nothing when $V = 8$. "+1" traders offer to buy when the tentative price reaches 2. "−1" uninformed traders do not offer to trade.

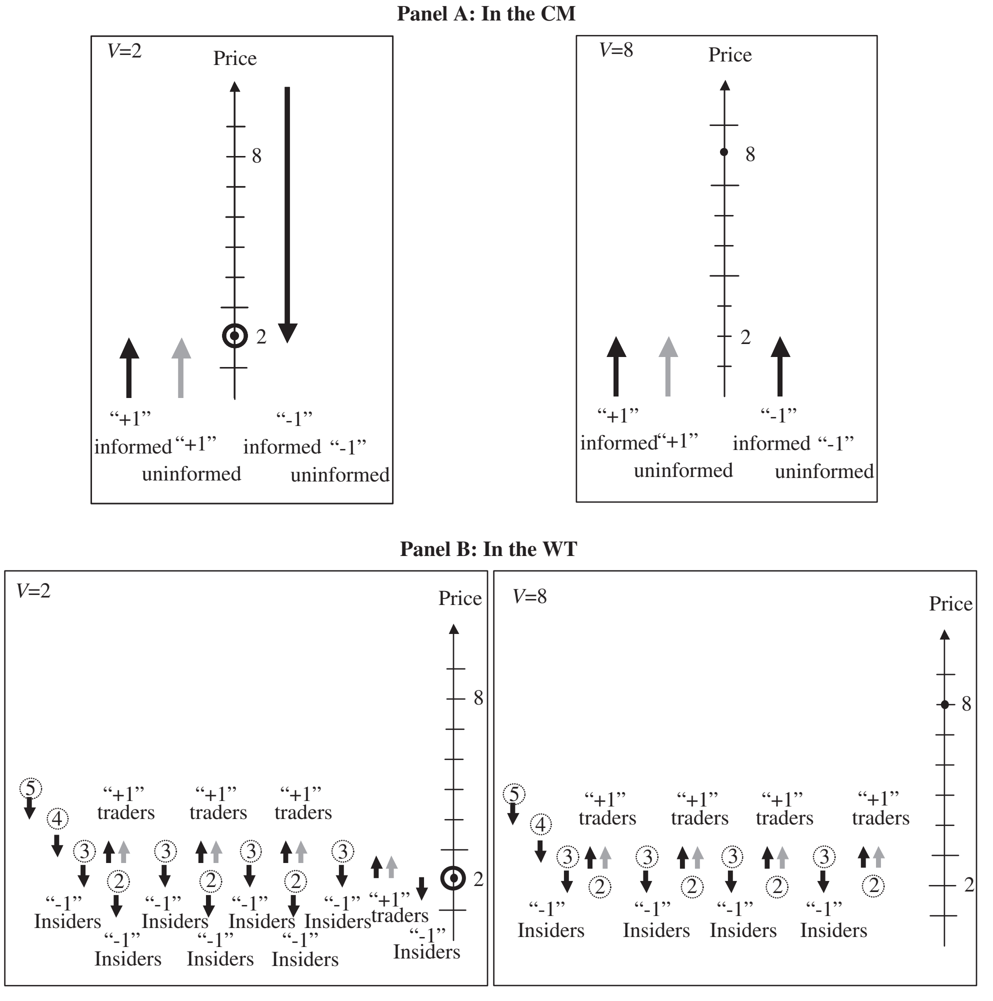

Fig. 2. Examples of partially revealing equilibrium strategies. Left boxes correspond to $V = 2$, right boxes to $V = 8$. Thick black circles indicate the transaction price (if it exists). Dotted circles in the WT indicate the successive tentative prices. Arrows pointing to the top (bottom) represent buying (selling) limit orders. The black (grey) color refers to informed (uninformed) traders.

I have designed the experiment so that equilibrium sets do not depend on the level of risk aversion. This independence is a reminiscence of the no-trade theorem stated by Milgrom and Stockey (1982). Since traders start each replication with no assets, there is no risk-sharing motive for transacting. Apart from the private value component of the payoff, the only trading motivation is related to private information. Anticipating this feature, uninformed traders will only be willing to trade at revealing prices.[11] In any case, they cannot incur losses at equilibrium.

[11]When trading motives are related to both risk sharing and private information, equilibrium outcomes depend on risk preferences (see, for example, Grossman and Stiglitz, 1980).

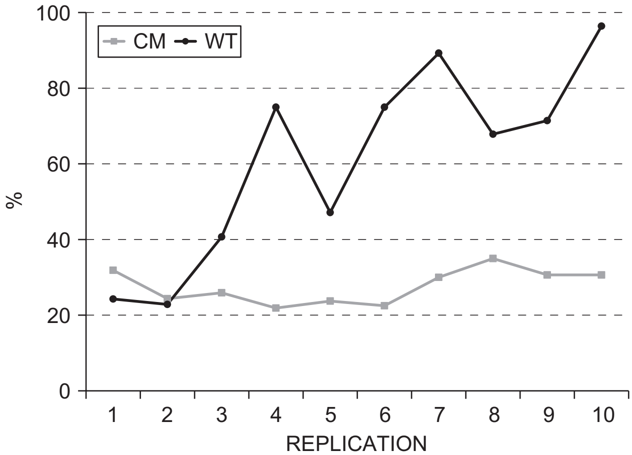

Fig. 3. Gains from trade. Gains from trade are measured by the total surplus earned (averaged across cohorts) as a proportion of the full extraction level.

3. Call Market vs. Walrasian Tatonnement

The objective of the present section is to study whether experimental observations are in line with theoretical predictions. I start by studying the allocative efficiency of the two market institutions.[12] Allocative efficiency is measured by the realized gains from trade compared to the full extraction level. Fig. 3 presents the evolution of the cross-cohort average of the gains from trade over the ten replications. Gains from trade are initially quite low on both the CM and the WT. However, on the latter market institution, gains from trade rise over the last five replications and almost reach the full extraction level.

These graphical impressions are confirmed by data presented in Table 1. During the first five replications, mean gains from trade (MGFT) equal 28% of the full extraction level on the CM, and 50% on the WT.[13] These proportions appear quite low. The difference between the CM and the WT is only marginally significant: a rank sum test for the difference in median for the MGFT on the two market institutions generates a p-value of 0.083. During the last five replications, median MGFT are 30% of the full extraction level on the CM and 80% on the WT.[14] The difference between the CM and the WT is statistically significant with a p-value of 0.001.

There are weak signs of an increase in the gains from trade on the CM: the cross-cohort median evolution in MGFT between the last and the first five replications is 5%, and this evolution is statistically positive with a sign test p-value of 0.031. On the contrary, there is evidence of a strong increase of the gains from trade extracted on the WT: the increase in the cross-cohort median MGFT from the first to the last five replications is 36%, and this

[12]Results on trading volume are qualitatively similar.

[13]MGFT are between 12% and 35% with a 93% confidence, and between 15% and 64% with a 98% confidence for the CM and the WT, respectively.

[14]MGFT are between 20% and 35% with a 93% confidence, and between 70% and 95% with a 98% confidence for the CM and the WT, respectively.

Table 1
Evolution of the mean gains from trade (MGFT) as a proportion of the full extraction level, and the mean absolute deviation (MAD) between prices and common values

This table displays the MAD and the MGFT during the first and the last 5 replications, and the difference between the latter and the former.

	Cohorts	Mean gains from trade (MGFT) as a proportion of full extraction level			Mean absolute deviation (MAD) between prices and common values		
		First 5 replications (1)	Last 5 replications (2)	Evolution (3) = (2)-(1)	First 5 replications (4)	Last 5 replications (5)	Evolution (6) = (5)-(4)
CM	1008011	30	35	5	0.8	0.6	−0.2
	1008012	35	20	−15	0.2	0.6	0.4
	1015011	25	30	5	0.4	0.6	0.2
	1022011	40	45	5	0.6	0.6	0.0
	1026001	25	30	5	1.2	0.6	−0.6
	1026002	8	15	8	2.4	1.2	−1.2
	1026003	30	35	5	0.8	0.6	−0.2
	1030001	12	28	16	1.6	0.8	−0.8
	Median	28	30	5	0.8	0.6	−0.2
WT	1003011	60	95	35	0.4	0.0	−0.4
	1003012	50	70	20	0.4	0.2	−0.2
	1003013	15	60	45	2.0	0.6	−1.4
	1003014	25	70	45	1.2	0.6	−0.6
	1030002	25	85	60	1.0	0.0	−1.0
	1102001	64	100	36	0.0	0.0	0.0
	1102002	55	80	25	0.6	0.2	−0.4
	Median	50	80	36	0.6	0.2	−0.4

evolution is significantly positive with a p-value of 0.008. Overall, these results suggest that, while the gains from trade are initially quite low on both market institutions, there is a strong convergence towards full extraction on the WT but not on the CM.[15]

One reason that total surplus appears higher on the WT than on the CM might be that traders on the two market institutions do not coordinate on the same equilibrium set. The results on allocative efficiency presented above could indeed suggest that traders on the CM coordinate on a partially revealing equilibrium while traders on the WT coordinate on a fully revealing equilibrium. As shown in Fig. 4 and in Table 1, prices on both market structures appear strong-form efficient: the absolute deviation between the price and the common value of the asset is in the fully revealing range, i.e., it is close to or smaller than one. The mean absolute deviation (MAD) on the CM is smaller than 1.6 and 0.8 during the first and last five replications, respectively, with a 97% confidence. The MAD on the WT is smaller than 1.2 with a 95% confidence during the first five replications, and is smaller than 0.6 with a 99% confidence during the last five replications. This pricing pattern is consistent with the fact that insiders on both market institutions coordinate on a fully revealing equilibrium. However, it could also be obtained if insiders were coordinating on

[15]Appendix C offers more detail about the tatonnement process on the WT. It shows in particular that the market needs more than five iterations before clearing because traders try (but fail) to influence the tatonnement process in their advantage.

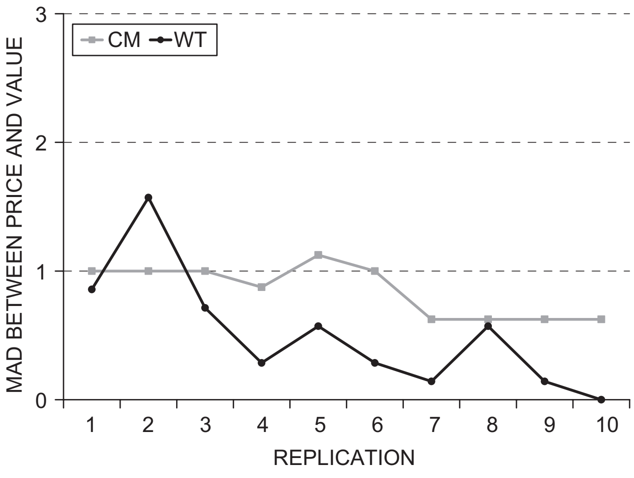

Fig. 4. Price efficiency. Price efficiency is measured by the cross-cohort mean absolute deviation (MAD) between the price and the common value of the asset.

a partially revealing equilibrium. In that case, there is indeed a probability of 1/2 that the price is in the revealing range. To speak to this issue, I construct the following test. For each replication, I code 1 when the price is greater (respectively smaller) than 5 and the value is high (respectively low), and 0 otherwise. I then compute the likelihood of observing the data if agents coordinate on a partially revealing equilibrium. This likelihood follows a binomial distribution.[16] On the CM, it ranges from 0.004 to 0.031, and equals on average 0.009. On the WT, it ranges from 0.008 to 0.164, and equals on average 0.033. Overall, this likelihood appears very low, and the hypothesis that traders coordinate on the partially revealing equilibria thus appears improbable. Two remarks help to understand why insiders choose to coordinate on revealing equilibria. First, an insider's surplus is maximal at a fully revealing equilibrium. Second, playing a revealing strategy never exposes insiders to losses (even if other traders coordinate on a partially revealing equilibrium).

Why does the Walrasian Tatonnement perform better than the CM? The only element that is not controlled by the experimenter is subjects' cognition.[17] Consequently, the only admissible reasons that equilibrium may not arise in the experiment are related to limitations on agents' cognitive capacities. These limits may influence traders' behavior in two ways. Various bounds on cognition may directly be at the basis of the observed behavior: one can think of non-rational expectations (see Williams, 1987), unsystematic errors (Stanovitch and West, 2000), judgmental biases (Biais, Hilton, Mazurier and

[16]Define a hit as the fact that the price is higher (lower) than 5 when the value is high (low). Under the null hypothesis that prices are set randomly or that traders coordinate on partially revealing equilibria, the probability of a hit is 1/2. (Alternatively, if traders coordinate on the fully revealing equilibria, the probability of a hit is 1.) The likelihood of obtaining the observed number of hits under the null hypothesis thus follows a binomial distribution (where the probability of observing a success is 1/2). If this likelihood is low enough, one can reject the fact that agents coordinate on partially revealing equilibria and that prices are set randomly.

[17]Another element that is not controlled is subjects' preferences. However, this should not influence interpretations since the theoretical benchmark, for all equilibria, is independent from the degree of risk aversion.

Pouget, 2005), or computational limitations (Pingle and Day, 1993). I refer to this direct effect as bounded rationality. Limits on cognitive capacities may also indirectly influence traders' behavior: to the extent that an agent does not know with certainty whether other players are going to play equilibrium, she faces additional uncertainty that may render useless the choice of an equilibrium strategy. I refer to this indirect effect as strategic uncertainty.[18,19]

In this context, market design can have a dual influence on market performance. First, following Camerer and Hogarth (1999), choosing a particular market structure may be viewed as designing traders' task. Various tasks may differ in terms of mental representations (see Camerer, 1999). As long as different market structures generate different mental representations, some market structures may be less demanding than others in terms of cognitive abilities. During the CM, when designing their orders, traders do not know the transaction price: they have to reason and to put themselves, for each price level, in a situation where a transaction would occur. On the opposite side, during a WT, agents can observe the successive tentative prices and thus can experience the law of supply and demand. The greater simplicity of the WT relative to the CM is related to its price-driven nature and to the use of market orders instead of limit orders.

Second, traders on the WT know the potential trading price before transacting. They can easily figure out whether this price is consistent or not with equilibrium. Traders can thus avoid transacting at non-equilibrium prices. Such a protection against strategic uncertainty is not available on the CM where, to play a fully revealing equilibrium strategy, uninformed traders have to submit aggressive limit orders that expose them to trading at out-of-equilibrium prices. If they want to protect themselves from strategic uncertainty, uninformed traders on the CM have to deviate from fully revealing equilibrium strategies and submit conservative orders.

These two interpretations are in line with the theoretical analysis of Pouget (2007). In this analysis, traders' behavior evolves via reinforcement learning, and a WT performs better than a CM. Pouget (2007) shows that this result is due to two features offered by the WT and mentioned above. Cognitive simplicity enables agents to learn faster the appropriate strategies, and protection against strategic uncertainty reduces the noise learning agents have to cope with.

4. Bounded rationality vs. strategic uncertainty

This section aims at confirming the validity of the interpretations provided above. It addresses the following questions: does strategic uncertainty really play a role in the

[18]In the present experimental framework, strategic uncertainty could also emerge because of problems of coordination across the two equilibrium sets. However, since we consistently observe a fully revealing pricing, bounded rationality appears to be the most plausible source of strategic uncertainty.

[19]In the fully revealing equilibrium, uninformed traders can free-ride on the fact that competition among the informed traders forces them to reveal the correct value and, thus, leads to efficient price discovery. However, for this to happen in practice, uninformed traders face two problems. One is mechanical: what orders should they submit to free-ride the price discovery process without disrupting it? The other is strategic: how confident are the uninformed traders that they can rely on competition to prevent the informed traders from taking advantage of them? Presumably, the fewer informed traders in the market, the less confident the uninformed will feel. In that sense, my analysis focuses on realistic but worst case scenarios with the absolute minimum possible informed competition.

experiment?[20] If so, what is its relative impact on allocative efficiency compared to bounded rationality?

One way to answer the first question is to study more precisely the type of behavior traders adopt on the CM where strategic uncertainty is likely to play a significant role. I classify subjects' actions into four categories, Actions I, II, III, and IV. These categories correspond to different types of trading outcomes. Action I corresponds to the fully revealing equilibrium strategy. Action II cannot generate losses but is sub-optimal if prices are fully revealing: it protects uninformed traders from strategic uncertainty but prevents them from participating in all the transactions that are profitable if prices are revealing.[21] Action III induces no participation in transactions. Action IV corresponds to potential loss-making orders.

Appendix E displays the classification for a "+1" uninformed trader.[22] The menu of orders "buy at prices up to 10 and sell at prices up to 10" is part of Action I. Indeed, this menu is equivalent to an order to buy at prices up to 9, and is part of "+1" uninformed traders' fully revealing strategies discussed in Section 2. The menu of orders "buy at prices up to 10 and sell at prices up to 4" which is equivalent to an order to buy at prices up to 3, is part of Action II. When $V = 2$, this menu enables a "+1" uninformed trader to buy if the price is in the revealing range (i.e., if the price is 1, 2, or 3) but not if it is outside this range (i.e., if the price is 4, 5, 6 or higher). A drawback of this menu is that, it does not allow the uninformed trader to participate in transactions at revealing prices when $V = 8$. The menu of orders "buy at prices up to 10 and sell at prices up to 1" is part of Action III. Indeed, this menu corresponds to an order to buy at a price of 0 and has no chance to be executed. Finally, the menu of orders "buy at prices up to 10 and sell at prices up to 7" is part of Action IV. This menu is equivalent to an order to buy at prices up to 6, and exposes "+1" uninformed traders to the risk of buying at a price higher than 3, which is unprofitable when $V = 2$.[23]

The proportions of the various actions actually played during the experiment are in Table 2. If traders were randomly choosing one of the 121 menus of orders available, the proportions of Action I, II, III, and IV would be, for uninformed traders, 9%, 15%, 4%, and 72%, respectively, and, for insiders, 24%, 22%, 4%, and 50%, respectively. A chi-square test applied to the cross-cohort median proportions show that these proportions are

[20] I also show below that, less surprisingly, bounded rationality actually plays a role in the experiment.

[21] Since they know the realization of the common value, insiders cannot be hurt by strategic uncertainty. Action II is thus defined differently: it includes the menus of orders that can enable insiders to earn a higher surplus than the equilibrium surplus. However, these rent-seeking menus expose insiders to the risk of not trading at profitable prices. Appendix D displays the classification for a "+1" insider when $V = 8$. The menu of orders "buy up to a price of 10 and sell up to a price of 7", which is equivalent to an order to buy up to a price of 6, is part of Action II. If it is executed at a price of 6, it generates a surplus of 3. However, if the price is in the fully revealing range, for example if the price is 7, the menu of order does not enable the insider to participate in the transaction despite the fact that this transaction would have been beneficial.

[22] Classifications for "−1" uninformed traders, for "+1" insiders when $V = 2$, and for "−1" insiders follow the same logic.

[23] If an agent chooses to bet on a particular realization of the common value, this behavior would be coded either as action I or as action IV. Thus action I does not only include equilibrium actions. However for a given agent, if an action IV is found out after several actions I, these previous actions I are treated as action IV. This coding option refines the content of action I by screening out potential gambling behavior. It is based on the premise that if an uninformed agent has discovered the optimal strategy given that the insiders reveal their information, it seems not plausible that she would switch to a less profitable action.

not due to random behavior: p-values are smaller than 0.001 for the first and the last five replications for both uninformed traders and insiders. Uninformed traders' choices are concentrated on Actions II and IV meaning that some of them protect themselves from strategic uncertainty while others submit potentially loss-making orders. This result confirms that both bounded rationality and strategic uncertainty play a role in our experiment. Uninformed traders' Actions I, II, and III are slightly more frequent during the last five replications than during the first five (p-values of 0.094). Action IV's frequency significantly drops by 20% from the first to the last five replications (p-value of 0.004) but remains pretty high at 38%. These findings suggest that uninformed traders learn to avoid potentially loss-making orders. However, this learning not only favors fully revealing equilibrium actions but also actions that mitigate strategic uncertainty. This is consistent with the simulation results of Pouget (2007) showing that, with reinforcement learning, uninformed traders' behavior converges towards actions that prevent them from transacting at out-of-equilibrium prices.

Insiders' choices are initially concentrated on Actions I, II, and IV. There is strong evidence that insiders' behavior converges towards the fully revealing equilibrium strategy. Action II and Action IV frequencies decrease by 8% (p-value of 0.016) and 10% (p-value of 0.031), respectively; Action I's frequency increases by 18% (p-value of 0.004) and reaches 85%. Overall, these findings explain why I simultaneously observe fully revealing prices and low gains from trade on the CM: insiders play fully revealing equilibrium strategies while uninformed traders protect from strategic uncertainty by submitting conservative orders or refusing to trade altogether.

To measure the relative importance of bounded rationality and strategic uncertainty in the experiment, I study informed and uninformed traders' behavior on both market institutions. Since insiders are not subject to strategic uncertainty, comparing their behavior on the CM and on the WT enables me to assess the influence of the CM complexity. Comparing uninformed and informed traders' behavior on the CM enables me to estimate the incremental impact of strategic uncertainty. Uninformed traders' task may however be more complex than insiders'. To account for this effect, I use the WT as a benchmark. Indeed, since there is no strategic uncertainty on the WT, the difference in behavior between uninformed and informed traders can be attributed to an increase in task complexity.

To estimate the loss of allocative efficiency due to bounded rationality and strategic uncertainty, Table 3 presents the gains from trade extracted by uninformed and informed traders on both market institutions.[24] Focusing on the last five replications, the median proportion of surplus extracted by insiders is 100% of the full extraction level on the WT and 65% on the CM. On the WT, the median proportion of surplus extracted is only 65% for uninformed traders, and is statistically different from insiders' surplus (the p-value is 0.01). Finally, the median proportion of surplus extracted by uninformed traders on the CM is -13%, and is significantly different from insiders' surplus extraction (the p-value is smaller than 0.001).[25] Overall, this analysis suggests that the proportion of surplus realized

[24]I have repeated the same type of analysis on other variables such as the ability of identical agents to trade identically (as they should at a symmetric equilibrium), and the ability of traders to participate in transactions (as they should at a fully revealing equilibrium). The results are qualitatively similar.

[25]The fact that uninformed traders on the CM earn a negative surplus indicates that the uninformed traders who are choosing Action IV are not only risking losing money but are actually losing money.

Table 2
Traders' actions on the Call Market

This table classifies traders' actions into four categories. Action I corresponds to the fully revealing equilibrium strategy, Action II does not generate losses but is sub-optimal, Action III induces no transaction, and Action IV includes potential loss-making strategies. Medians are computed across cohorts.

	Cohorts	Average proportion for uninformed traders			Average proportion for insiders		
		First 5 replications (1) (%)	Last 5 replications (2) (%)	Evolution (3) = (2)-(1) (%)	First 5 replications (4) (%)	Last 5 replications (5) (%)	Evolution (6) = (5)-(4) (%)
Action I	1008011	5	5	0	80	95	15
	1008012	0	0	0	70	85	15
	1015011	5	0	−5	40	85	45
	1022011	0	10	10	85	95	10
	1026001	0	10	10	50	70	20
	1026002	5	10	5	35	65	30
	1026003	0	15	15	90	90	0
	1030001	0	7	7	43	77	33
	Median	0	8	6	60	85	18
Action II	1008011	35	45	10	5	5	0
	1008012	25	45	20	25	10	−15
	1015011	35	60	25	45	15	−30
	1022011	35	35	0	5	0	−5
	1026001	35	25	−10	40	30	−10
	1026002	20	20	0	35	30	−5
	1026003	40	50	10	10	5	−5
	1030001	10	27	17	30	7	−23
	Median	35	40	10	28	8	−8
Action III	1008011	0	10	10	5	0	−5
	1008012	20	20	0	0	5	5
	1015011	10	20	10	5	0	−5
	1022011	35	30	−5	0	0	0
	1026001	10	25	15	0	0	0
	1026002	0	0	0	0	0	0
	1026003	0	5	5	0	0	0
	1030001	7	17	10	0	3	3
	Median	8	18	8	0	0	0
Action IV	1008011	60	40	−20	10	0	−10
	1008012	55	35	−20	5	0	−5
	1015011	50	20	−30	10	0	−10
	1022011	30	25	−5	10	5	−5
	1026001	55	40	−15	10	0	−10
	1026002	75	70	−5	30	5	−25
	1026003	60	30	−30	0	5	5
	1030001	83	50	−33	27	13	−13
	Median	58	38	−20	10	3	−10

by uninformed traders on the CM goes (i) from 100% of the full extraction level to 65% because of the complexity of the Call Market, (ii) from 65% to 30% because of the complexity of the task faced by uninformed traders (this 35% difference comes from the

Table 3
Mean gains from trade (MGFT) realized by uninformed and informed traders
This table reports the MGFT during the first and the last 5 replications, and the difference between the latter and the former.

	Cohorts	Uninformed traders' mean gains from trade			Insiders' mean gains from trade		
		First 5 replications (1) (%)	Last 5 replications (2) (%)	Evolution (3) = (2)-(1) (%)	First 5 replications (4) (%)	Last 5 replications (5) (%)	Evolution (6) = (5)-(4) (%)
CM	1008011	0	15	15	60	55	−5
	1008012	20	−15	−35	50	55	5
	1015011	15	−15	−30	35	75	40
	1022011	−5	0	5	85	90	5
	1026001	−20	−10	10	70	70	0
	1026002	−75	−25	50	90	55	−35
	1026003	−15	10	25	75	60	−15
	1030001	−48	−25	23	77	97	20
	Median	−10	−13	13	73	65	3
WT	1003011	40	90	50	80	100	20
	1003012	10	50	40	90	90	0
	1003013	−75	5	80	105	115	10
	1003014	−55	40	95	105	100	−5
	1030002	−5	85	90	55	85	30
	1102001	53	100	47	77	100	23
	1102002	20	65	45	90	95	5
	Median	10	65	50	90	100	10

difference between insiders' and uninformed traders' levels of extraction on the WT), and (iii) from 30% to −13% because of strategic uncertainty.

5. Conclusion

This paper studies market institutions' influence on equilibration in experimental financial markets. The analysis compares the performances of a Call Market and a Walrasian Tatonnement in a context in which both market institutions have similar equilibrium outcomes (prices and allocations). In the fully revealing equilibrium set, prices are strongly efficient and all the gains from trade are exploited.

During the experiment, the gains from trade are higher on the Walrasian Tatonnement than on the Call Market despite the fact that prices are fully revealing on the two market institutions. Uninformed traders on the Call Market do not participate in the Call Market trading process as much as predicted by theory because of bounded rationality and strategic uncertainty. These two factors significantly reduce the ability of traders to learn their equilibrium strategies.

Overall, this paper shows that limitations on human cognition can create transaction costs. Yet, adequate design of the market structure can overcome the impact of cognitive limits. In this experiment, compared to a Call Market, a Walrasian Tatonnement provides a way to economize on cognitive transaction costs. I explain the greater performance of the WT in terms of more tractable mental representations and robustness to strategic uncertainty, both features which foster learning. Hence, this paper suggests that even when it does not influence strategic outcomes, market design may still be an important source of efficiency gains through its effect on traders' ability to discover equilibrium.

Appendix A. Instructions to the subjects in the Walrasian Tatonnement

In this trading game you will have the opportunity to buy and sell shares. You will play 10 replications of the trading game. At the beginning of each replication you will receive 10 €. During the game you will have the opportunity to place orders to buy or sell the shares. (You can sell more shares than you own, i.e., short sales are allowed). At the end of each replication, you will compute the value of your final wealth, equal to the sum of: your initial cash: 10 €, minus the cost of your share purchases, plus the proceeds from your share sales, plus the final value of your portfolio. The final value of your portfolio is equal to the number of shares you own at the end of the replication, multiplied by the final value of each share. The final value of the shares is the sum of two elements.

The first element is a value that is common to all traders. This common value is drawn randomly (and independently from the previous draws). It can be 2 or 8, with equal probability 1/2.

The second element is a private value. This private value remains the same during all the replications. Half of the subjects have the private value +1 and the other half have the private value –1.

For example, if your only trade was the purchase of one share at price 6, the common value of the shares is 8, and your private value is −1, your final wealth is: $10-6+(8-1)=11$. In the same situation, if your private value is +1, your final wealth is: $10-6+(8+1)=13$. Since you can sell more shares than you own, you can end up with a negative number of shares held at the end of the replication. For example, if you sold 1 share at price 4, the common value of the shares is 2, and your private value is +1, your final wealth is: $10+4-(2+1)=11$. In the same situation, if your private value is −1, your final wealth is: $10+4-(2-1)=13$.

At the beginning of each replication, half of the agents will receive a piece of private information (keep it secret, don't reveal it to the others !). This private information reveals perfectly the common value of the shares.

Trading proceeds as follows.

Step 1: the auctioneer announces a price P which is equal to the unconditional expectation of the common value element. $P=1/2\times 2+1/2\times 8=5$.

Step 2: you can place an order to buy or to sell one share at the announced price. If the aggregate supply S equals the aggregate demand D, a transaction occurs at the announced price, the common value is publicly revealed and final wealth is computed. If not, we proceed to step 3.

Step 3: a new price P' is announced. This price is computed as follows: $P' = P+1$ when $D>S$ and $P' = P-1$ when $D<S$, where P is the previously announced price. We then proceed to step 2.

After the 10th announcement, even if supply and demand are not equal, a transaction occurs. If $D>S$, $(D–S)$ buyers are randomly rationed. If $D<S$, $(S–D)$ sellers are randomly rationed.

The grade for the course is between 0 and 20. Students participating in 10 replications of the game will earn bonus points (to be added to their final exam grade to determine the course grade) computed as

$$\left[\frac{\sum_{t=1}^{10} W_t - 98}{2}\right]^+,$$

where W_t represents the final wealth of the subject at the end of replication t. Your private value is $+1$.

Appendix B. Equilibrium analysis

I focus on pure strategies, symmetric equilibria with a non-null expected trading volume. I consider that there are 8 traders on the market, indexed by $i \in 1,2,\ldots,8$, but the analysis can be extended to the 10-player case. By convention, agents 1 and 2 are "$+1$" insiders, agents 3 and 4 are "-1" insiders, agents 5 and 6 are "$+1$" uninformed traders, and agents 7 and 8 are "-1" uninformed traders. Denote all agents other than i by $-i$. Assume that agents have utility functions $U_i(.)$ that are increasing and concave. Note that agents are not assigned a specific utility function nor a particular degree of risk aversion. Let Q equal 1 indicate a purchase and Q equal -1 indicate a sale. Let $X(.)$ be the excess demand, and $Y(.)$ the absolute excess demand: $Y(.) = \text{abs}[X(.)]$. Let $e(.)$ be the probability that an order is executed. Let $e(.)$ equal $e_b(.)$ for buy orders , and $e_s(.)$ for sell orders.

Let's begin by defining the strategies and the equilibrium concept for the Call Market. The strategy space for each player i is a set $\{0,1,\ldots,10\} \times \{0,1,\ldots,10\}$ with elements $\{b_i,s_i\}$ representing limit prices to buy and to sell, respectively. An insider's strategy is a mapping $\{b_i,s_i\}:\{2,8\} \rightarrow \{0,1,\ldots,10\} \times \{0,1,\ldots,10\}$ that prescribes limit prices to buy and sell on the basis of insider's private information V. A Bayesian equilibrium in the CM is a strategy profile $(\{b_i,s_i\},\{b_{-i},s_{-i}\})$ such that, given $\{b_{-i},s_{-i}\}$, $U_i(\{b_i,s_i\},\{b_{-i},s_{-i}\}) > U_i(\{b_i', s_i'\}, \{b_{-i},s_{-i}\})$ for all b_i', s_i' and i.

Let's define now the strategies and the equilibrium concept for the Walrasian Tatonnement. Denote by t each round of the tatonnement process with $t \in \{1,2,\ldots,10\}$. Denote by H_t the observable history of the market at the beginning of round t (i.e., the sequence of past tentative prices, from P_1 through P_{t-1}). At each round t, the strategy space is a set of actions $\{-1,0,1\}$ indicating whether the agent wants to sell, do nothing, or buy, respectively. An insider's strategy is a mapping S_i: $P_t \times \mathrm{H}_t \times \{2,8\} \rightarrow \{-1,0,1\}$, for all t, that prescribes an order to sell, do nothing, or buy on the basis of the current tentative price, the market history and his private information V. An uninformed trader's strategy is a mapping S_i: $P_t \times \mathrm{H}_t \rightarrow \{-1,0,1\}$, for all t, that prescribes an order to sell, do nothing, or buy on the basis of the current tentative price and the market history. The conditional beliefs of the uninformed traders are represented by a mapping that associates to each current tentative price P_t and market history H_t a probability function $g[.\backslash P_t, H_t]$ on $\{2,8\}$, where $g[V = v\backslash P_t, H_t]$ is the probability that the uninformed trader attaches to $V = v$ given the current tentative price P_t and the market history H_t. A perfect Bayesian equilibrium in the WT is a strategy profile (S_i,S_{-i}) and a family of conditional beliefs $g[.\backslash.]$ such that, given S_{-i}, $U_i(S_i,S_{-i}) > U_i(S_i',S_{-i})$ for all i and S_i', and such that $g[.\backslash P_t, H_t]$ is the conditional probability of V obtained by updating the prior (1/2,1/2) using P_t and H_t in a Bayesian fashion.

The first two lemmas establish that, in some circumstances, it is not possible for traders to individually influence price formation on the CM and on the WT. The proofs of these lemmas mainly rely on the fact that traders can only place orders for one unit of asset. This feature prevents traders from individually destabilizing the trading process by demanding or offering large quantities.

Lemma 1. No veto power on the CM

On the CM, if traders coordinate on submitting demand schedules so that there is a unique market-clearing price P, i.e., there is only on price P where $Y(P) = 0$, and so that the absolute excess demand $Y(.)$ is greater than or equal to 2 at P-1 and $P+1$, no trader can influence the price without foregoing the opportunity to participate in the transaction or without obtaining worse execution conditions.

Proof. Consider demand schedules such that $Y(P\text{-}1)\geqslant 2$, $Y(P) = 0$, and $Y(P+1)\geqslant 2$.

The objective is to prove that no unilateral deviation can allow a trader to modify the transaction price to her advantage. I focus on a buyer's deviation. By symmetry, the same reasoning applies for a selling trader's deviation.

Let's start by analyzing the situations where a deviation does not modify the transaction price. This is the case when (i) a trader whose limit price is P deviates by increasing her limit price; (ii) a trader whose limit price is equal to P decreases her limit price to P-1; (iii) a trader whose limit price is P-1 increases her limit price to P; (iv) a trader whose limit price is strictly smaller than P-1 increases her limit price to P-1 or P; (v) a trader whose limit price is greater than or equal to $P+1$ decreases her limit price to P or P-1.[26] In all these cases, P remains the price that minimizes the excess demand and thus it remains the transaction price.

Let's now analyze the situations where a deviation does modify the transaction price but prevents the trader from participating in the transaction. This situation corresponds to a buying trader whose limit price is equal to P and who wants to deviate by decreasing her limit price to P-n with $n>1$. In this case, $Y(P\text{-}1)\geqslant 1$, $Y(P) = 1$, and $Y(P+1)\geqslant 2$. The trading price has a chance to be P-1 instead of P, but the deviating trader will not be part of the transaction.

Finally, let's discuss the cases where deviating moves the price against the trader's interest. Consider a buying trader whose limit price is P-1 or lower. If she increases her limit price to $P+1$, the absolute excess demands become $Y(P\text{-}1)\geqslant 2$, $Y(P) = 1$, and $Y(P+1)\geqslant 1$. The transaction price will thus be greater than or equal to P. □

Lemma 2. No veto power on the WT

On the WT, as long as the absolute excess demand is greater than or equal to 2, no trader has an influence on the price adjustment.

Proof. When the absolute excess demand is greater than or equal to 2, traders cannot individually affect the sign of the excess demand (remember that they can only submit orders for one unit of the asset). Since the WT process only relies on the sign of

[26]To see that the transaction price is not affected by the deviation described in i), remark that, after the deviation, the absolute excess demands are $Y(P\text{-}1)\geq 2$, $Y(P) = 0$, and $Y(P+1)\geq 1$, and thus P remains the price that minimizes the absolute excess demand. The same logic applies to the other deviations.

the excess demand and not on its magnitude, no trader can influence the evolution of tentative prices. □

Before analyzing the asymmetric information case, it is useful to consider what happens when all traders know the common value of the asset. This is stated in the next proposition.

Proposition 1. *Equilibrium under perfect information*

If the common value of the asset (V) is common knowledge among traders, at the Nash equilibrium on both the CM and the WT, "+1 traders" buy from "-1 traders", and transactions occur at a price of 1, 2, or 3 when $V=2$, and at a price of 7, 8, or 9 when $V=8$.

Proof. The individual rationality constraint of the "+1 traders" is:

IR(+1): $U_i[Q \times \mathrm{e} \times (V+1\text{-}P)] \geqslant U_i(0)$.

Since $U_i(.)$ is increasing, IR(+1) holds if and only if $Q \times \mathrm{e} \times (V+1\text{-}P) \geqslant 0$. IR(+1) can thus be written in the case of a purchase:

IR(+1)': $P \leqslant V+1$.

In the case of a sale, it can be written:

IR(+1)'': $P \geqslant V+1$.

Following the same logic, the individual rationality constraint of the "-1 traders", IR(-1), can be written in the case of a purchase:

IR(-1)': $P \leqslant V\text{-}1$.

In the case of a sale, it can be written:

IR(-1)'': $P \geqslant V\text{-}1$.

Since IR(+1)'' and IR(-1)' cannot be jointly satisfied, no equilibrium exists where "+1 traders" sell to "-1 traders".

The price restriction stated in the proposition is obtained by combining IR(+1)' and IR(-1)''. They imply that $V\text{-}1 \leqslant P \leqslant V+1$.

The fact that there is only one trading opportunity rules out any potential market manipulation. This indicates that agents will accept transactions occurring at prices lying between V-1 and $V+1$, with "+1 traders" buying from "-1 traders". It is straightforward to show that there exists strategies on the CM and on the WT that sustain these equilibrium outcomes. □

At the fully revealing equilibria, traders learn what the common value of the asset is during the trading process. They thus end up in a situation which is similar to the perfect information case described above. This is stated in the following proposition.

Proposition 2. *Fully revealing equilibria*

In the CM and in the WT, there exists a unique class of fully revealing equilibria where the price of the asset is 1, 2, or 3 when $V=2$, and 7, 8, or 9 when $V=8$.

Proof. Fully revealing equilibria correspond to a situation where insiders' information is transmitted to uninformed agents through the trading process. At the time of the transaction, agents' beliefs are such that the value of the asset is common knowledge. Following Proposition 1, in such a case, the only individually rational prices are 1, 2, or 3 when $V=2$, and 7, 8, or 9 when $V=8$.

Such fully revealing equilibria will be achieved as soon as traders coordinate on these equilibria following the restrictions imposed in Lemmas 1 and 2. Since no deviation will have an impact on the trading process (with the deviating trader still participating in the transaction at a better price) and since traders can only submit one-unit orders, no deviation is profitable.

The existence of a strategy profile sustaining these equilibria on the CM and the WT is supported by the examples provided in Section 2 and illustrated in Fig. 1. For the WT, uninformed traders' conditional beliefs that sustain the equilibrium are the following. If $P_{t-1} \in [1,2,\ldots,9]$ and $P_t \in [1,2,\ldots,9]$, then $\mathrm{g}[2 \backslash H_{t-1}, P_{t-1}, P_t] = 1$ whenever $P_{t-1} > P_t$, and $\mathrm{g}[2 \backslash H_{t-1}, P_{t-1}, P_t] = 0$ whenever $P_{t-1} < P_t$. Otherwise, uninformed traders do not update their beliefs.

These examples of strategies satisfy the restrictions imposed in Lemmas 1 and 2. Overall, the equilibrium outcomes are the following. When $V = 2$, the transaction price is 2, 4 asset units are traded, and all the gains from trade are exploited (i.e., the total surplus is equal to 8). When $V = 8$, the transaction price is 8, 4 asset units are traded, and all the gains from trade are exploited (the total surplus is again equal to 8). It is straightforward to check that no unilateral deviation is profitable. □

Let's now characterize the partially revealing equilibria. To do so, it is useful to study insiders' behavior. The following lemma shows that, in some circumstances, insiders take identical positions to try to profit from their information.

Lemma 3. Insiders' behavior

When the transaction price is 4, 5 or 6, insiders trade in the same direction: if $V = 2$, they sell, and if $V = 8$, they buy.

Proof. Insiders' objective is to maximize their expected utility given (what they expect concerning) the demands of the other traders. Given a strategy profile that generates an execution probability e and a transaction price P, a "+1" insider's expected utility is given by $U_i[Q \times \mathrm{e} \times (V+1\text{-}P)]$ since she knows the realization of V. Consider that $V = 2$ and that $P = 4$ (the cases where $P = 5$ and 6 follow the same logic). Insider's expected utility is now $U_i[-Q \times \mathrm{e}]$. Since e is a probability, it is non-negative; in order to maximize her expected utility, the insider has to sell, i.e., she has to set $Q = -1$. Consider now that $V = 8$ and that $P = 4$ (again, the cases where $P = 5$ and 6 follow the same logic). The "+1" insider's expected utility is $U_i[5Q \times \mathrm{e}]$ and it is maximal for $Q = 1$. A "−1" insider's expected utility is given by $U_i[Q \times \mathrm{e} \times (V\text{-}1\text{-}P)]$ since she knows the realization of V. Consider that $V = 2$ and that $P = 4$ (the cases where $P = 5$ and 6 follow the same logic). Insider's expected utility is now $U_i[\text{-}3Q \times \mathrm{e}]$. Again, since e is a probability, it is non-negative; In order to maximize her expected utility, the insider has to sell, i.e., she has to set $Q = -1$. Consider now that $V = 8$ and that $P = 4$ (again, the cases where $P = 5$ and 6 follow the same logic). The "−1" insider's expected utility is $U_i[3Q \times \mathrm{e}]$ and it is maximal for $Q = 1$. If they anticipate that the price will be 4, 5, or 6, "+1" and "−1" insiders have the same desired positions. Furthermore, as their information is only valid for a unique market period, insiders will be willing to trade and profit from their information as soon as the price of the asset is not equal to its fundamental value, i.e., when it is not in the fully revealing range. □

This lemma precludes the existence of equilibrium with a transaction price of 4, 5, or 6.

Proposition 3. *Non-existence of equilibrium*

There exists no equilibrium with transaction prices of 4, 5 and 6.

Proof. We have already seen that a fully revealing equilibrium occurs at prices of 1, 2, or 3 when $V = 2$, and at prices of 7, 8, or 9 when $V = 8$. There is thus no fully revealing equilibrium with transaction prices between 4 and 6.

Let's prove that there is no non-revealing equilibrium in this price range. Let the transaction price P be equal to 4, 5, or 6. At a non-revealing equilibrium, uninformed traders' prior beliefs are not updated. A necessary condition for an allocation and a transaction price to be a non-revealing equilibrium is to satisfy the individual rationality (IR) constraints of the uninformed agents. For "+1" uninformed traders, this constraint is:

IR(+1,uninf): $1/2 \times U_i[Q \times \mathrm{e}(2) \times (2+1\text{-}P)] + 1/2 \times U_i[Q \times \mathrm{e}(8) \times (8+1\text{-}P)] \geqslant U_i(0)$.

For a buying "+1" uninformed trader, this constraint can be written:

IR(+1,uninf)': $1/2 \times U_i[e_\mathrm{b}(2) \times (2+1\text{-}P)] + 1/2 \times U[e_\mathrm{b}(8) \times (8+1\text{-}P)] \geqslant U_i(0)$.

Consider first the case where uninformed traders are on the buying side of the market. In this case, Lemma 3 implies that $e_\mathrm{b}(8) = 0$ since, when $V = 8$, all the insiders are on the buying side. Replacing $e_\mathrm{b}(8)$ by 0 in IR(+1,uninf)' yields:

IR(+1,uninf)': $U_i[e_\mathrm{b}(2) \times (2+1\text{-}P)] \geqslant U_i(0)$.

$U_i(.)$ being an increasing function and $e_\mathrm{b}(.)$ being non-negative, this IR constraint cannot be satisfied when $P > 3$. Following the same type of arguments, one can show that the IR constraint of a buying "−1" uninformed trader cannot be satisfied when $P > 1$. This implies that no non-revealing equilibrium exists with uninformed traders buying and with prices greater than 1.

Consider next that the two "+1" uninformed traders buy and that the two "−1" uninformed traders sell. As a result, $e_\mathrm{b}(8) = 2/6$ and $e_\mathrm{b}(2) = 1$. Replacing $e_\mathrm{b}(8)$ by 2/6 and $e_\mathrm{b}(2)$ by 1 in IR(+1,uninf)' yields:

IR(+1,uninf)': $1/2 \times U_i[(2+1\text{-}P)] + 1/2 \times U_i[2/6 \times (8+1\text{-}P)] \geqslant U_i(0)$.

Consider the extreme case of risk neutrality. The constraint becomes $P \leqslant 9/2$.

For the selling "−1" uninformed traders, the IR constraint assuming risk neutrality is $P \geqslant 11/2$.

These two constraints cannot be jointly satisfied. If this is true for risk neutral agents, it is also true for risk-averse agents. This is because, if a risk neutral agent rejects a lottery, then this lottery is also rejected by a risk-averse agent. This implies that a non-revealing equilibrium does not exist with the two "−1" uninformed traders selling and the two "+1" uninformed traders buying. The same arguments can be used to show that a non-revealing equilibrium does not exist when some uninformed traders do not submit any orders.

Now if the "+1" uninformed traders are selling to the "−1" uninformed traders, $e_\mathrm{s}(8) = 1$ and $e_\mathrm{s}(2) = 2/6$. Following the above reasoning, one can show that this situation does not constitute a non-revealing equilibrium.

If uninformed traders are on the selling side, one can show that the IR constraint of a selling "+1" uninformed trader cannot be satisfied when $P < 9$, and that the IR constraint of a selling "−1" uninformed trader cannot be satisfied when $P < 7$.

Overall, the combination of the IR constraints establishes the nonexistence of a non-revealing equilibrium when the transaction price is equal to 4, 5 and 6. □

The characterization of the partially revealing equilibrium set is available upon request. An example of a partially revealing equilibrium strategy profile is offered in Fig. 2.

Appendix C. Equilibration process on the Walrasian Tatonnement

Data and statistical tests supporting the results discussed in this paragraph are available upon request.

To provide more information on the equilibration process that leads to efficient allocations on the WT, I compare prices and surpluses in replications where the WT stopped at or before the fifth iteration to those where it stopped after the fifth iteration. Price efficiency as well as gains from trade are similar in the two cases. For replications where the tatonnement stopped after the fifth replication, I also compare outcomes at the fifth replication and outcomes at the transaction. While price efficiency is similar in the two cases, gains from trade are higher at the time of the transaction.

These findings could indicate that subjects needed more iterations to learn and adjust their strategies. This interpretation is however at odds with the fact that the average number of iterations needed to complete a transaction does not decrease with experience. Instead, these results suggest that (some) subjects were trying to influence the price to be chosen within the fully revealing range. This is in their interest since the transaction price influences the repartition of the trading surplus. It is also feasible since, when demand is about to equal supply, a unilateral deviation can prevent the market clearing. Consider, for example, that a trader anticipates that, at the next announced price, there will be four buyers (including herself) and four sellers; she can prevent the market from clearing by refraining herself from submitting the buy order. As a consequence, there would be a negative order imbalance, the market would not clear, and a new and lower price would be announced.

Overall, this discussion suggests that on the WT, fully revealing equilibrium prices are reached rapidly (in less than five iterations) and allocative efficiency is achieved despite the fact that some traders strive to appropriate to themselves the largest possible share of the surplus.

Appendix D. Action classification for a "+1" insider when $V = 8$ on the Call Market

Action I includes fully revealing equilibrium actions; Action II does not generate losses but is sub-optimal if prices are fully revealing; Action III is equivalent to not submitting any order; Action IV potentially generates losses.

Buy up to a price of	Sell up to a price of	ACTION
10	10	I
10	9	I
10	8	I
10	7	II
10	6	II
10	5	II
10	4	II
10	3	II
10	2	II
10	1	III
10	0	III

Buy up to a price of	Sell up to a price of	ACTION
9	10	I
9	9	I
9	8	I
9	7	II
9	6	II
9	5	II
9	4	II
9	3	II
9	2	II
9	1	III
9	0	III
8	10	I
8	9	I
8	8	I
8	7	II
8	6	II
8	5	II
8	4	II
8	3	II
8	2	II
8	1	II
8	0	II
7	10	I
7	9	I
7	8	IV
7	7	IV
7	6	IV
7	5	IV
7	4	IV
7	3	IV
7	2	IV
7	1	IV
7	0	IV
6	10	II
6	9	II
6	8	IV
6	7	IV
6	6	IV
6	5	IV
6	4	IV
6	3	IV
6	2	IV
6	1	IV

Buy up to a price of	Sell up to a price of	ACTION
6	0	IV
5	10	II
5	9	II
5	8	IV
5	7	IV
5	6	IV
5	5	IV
5	4	IV
5	3	IV
5	2	IV
5	1	IV
5	0	IV
4	10	II
4	9	II
4	8	IV
4	7	IV
4	6	IV
4	5	IV
4	4	IV
4	3	IV
4	2	IV
4	1	IV
4	0	IV
3	10	II
3	9	II
3	8	IV
3	7	IV
3	6	IV
3	5	IV
3	4	IV
3	3	IV
3	2	IV
3	1	IV
3	0	IV
2	10	II
2	9	II
2	8	IV
2	7	IV
2	6	IV
2	5	IV
2	4	IV
2	3	IV
2	2	IV

Buy up to a price of	Sell up to a price of	ACTION
2	1	IV
2	0	IV
1	10	II
1	9	II
1	8	IV
1	7	IV
1	6	IV
1	5	IV
1	4	IV
1	3	IV
1	2	IV
1	1	IV
1	0	IV
0	10	III
0	9	II
0	8	IV
0	7	IV
0	6	IV
0	5	IV
0	4	IV
0	3	IV
0	2	IV
0	1	IV
0	0	IV

Appendix E. Action classification for a "+1" uninformed trader on the Call Market

Action I includes fully revealing equilibrium actions; Action II does not generate losses but is sub-optimal if prices are fully revealing; Action III is equivalent to not submitting any order; Action IV potentially generates losses.

Buy up to a price of	Sell up to a price of	ACTION
10	10	I
10	9	I
10	8	I
10	7	IV
10	6	IV
10	5	IV
10	4	II
10	3	II
10	2	II

Buy up to a price of	Sell up to a price of	ACTION
10	1	III
10	0	III
9	10	I
9	9	I
9	8	I
9	7	IV
9	6	IV
9	5	IV
9	4	II
9	3	II
9	2	II
9	1	III
9	0	III
8	10	I
8	9	I
8	8	I
8	7	IV
8	6	IV
8	5	IV
8	4	II
8	3	II
8	2	II
8	1	II
8	0	II
7	10	I
7	9	I
7	8	IV
7	7	IV
7	6	IV
7	5	IV
7	4	IV
7	3	IV
7	2	IV
7	1	IV
7	0	IV
6	10	IV
6	9	IV
6	8	IV
6	7	IV
6	6	IV
6	5	IV
6	4	IV
6	3	IV

Buy up to a price of	Sell up to a price of	ACTION
6	2	IV
6	1	IV
6	0	IV
5	10	IV
5	9	IV
5	8	IV
5	7	IV
5	6	IV
5	5	IV
5	4	IV
5	3	IV
5	2	IV
5	1	IV
5	0	IV
4	10	IV
4	9	IV
4	8	IV
4	7	IV
4	6	IV
4	5	IV
4	4	IV
4	3	IV
4	2	IV
4	1	IV
4	0	IV
3	10	II
3	9	II
3	8	IV
3	7	IV
3	6	IV
3	5	IV
3	4	IV
3	3	IV
3	2	IV
3	1	IV
3	0	IV
2	10	II
2	9	II
2	8	IV
2	7	IV
2	6	IV
2	5	IV
2	4	IV

Buy up to a price of	Sell up to a price of	ACTION
2	3	IV
2	2	IV
2	1	IV
2	0	IV
1	10	II
1	9	II
1	8	IV
1	7	IV
1	6	IV
1	5	IV
1	4	IV
1	3	IV
1	2	IV
1	1	IV
1	0	IV
0	10	III
0	9	II
0	**8**	IV
0	7	IV
0	6	IV
0	5	IV
0	4	IV
0	3	IV
0	2	IV
0	1	IV
0	0	IV

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