Partial equilibrium mechanism and inter-sectoral coordination: an experiment*

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Abstract

This study experimentally evaluates the performance of partial equilibrium mechanisms when different sectors run their mechanisms separately, despite the existence of complementarity between them. In our simple laboratory experiment setting that includes two sectors, each sector runs the top-trading-cycle mechanism. There is a Pareto-dominant equilibrium, but it requires coordination across sectors. Our results show that coordination failure occurs more frequently when there is asymmetry between the two sectors compared with the one-sector benchmark, even without inter-sectoral complementarity. When mechanisms are run sequentially across the two sectors, such failure is substantially reduced, compared with when they are run simultaneously.

Keywords: Partial equilibrium, inter-sectoral coordination, top-trading-cycle mechanism, laboratory experiment

JEL Code: C92, D71, D82

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1 Introduction

This study experimentally evaluates the performance of partial equilibrium mechanisms when they are implemented in an institutionally realistic way. Different sectors run their mechanisms separately despite the existence of complementarity between them.

The utilization of virtually any good, in which term we include any service, is related to the utilization of other goods, and vice versa. Hence, apart from the consumption allocation of other goods, we cannot generically define a preference for the consumption of a single good or willingness to pay for it.

Therefore, in contrast to the presumption that accompanies operating partial equilibrium mechanisms in standard practice, we cannot isolate the issue of allocating a single good from the rest of the economy by assuming that other things remain equal. When we apply a partial equilibrium mechanism to some sectors based on such a false presumption, it will have an unintended effect on the other sectors. In addition, there must be mutual feedback across sectors because partial equilibrium mechanisms are adopted in many sectors of our society, and simultaneity among them is inevitable.

The partial equilibrium approach is justified when handling a sector that is small compared with an economy consisting of many sectors. In such a situation, the inter-sectoral dependence is negligible. This idea dates back to Marshall (1920), and it was formally proven later by Vives (1987). However, economically important problems are typically not minor, and the issue of inter-sectoral dependence is significant.

A prominent example is school choice and the housing market. Schools and houses are natural complements of each other because they are only valuable when they are in close proximity. Hence, one cannot have a “preference” over schools independently of one’s house, and vice versa. Thus, if we change something in the school allocation mechanism, it has been empirically shown that the housing market is affected (Bonilla-Mejía et al., 2020; Chung, 2015; Danielsen et al., 2015; Reback, 2005). Nevertheless, school choice programs commonly ask each household to submit only their school preference, while ignoring the complementarity with housing choice.

An ideal solution is for a central planner to solve the allocation problem for the economy. However, this is typically infeasible. Thus, we have to consider it a *given institutional constraint* that the economy is divided into many sectors, and each sector’s authority has a limited view in which agents only have preferences over objects in that sector. Such a division as the given institutional constraint results in agents determining how to achieve *inter-sectoral coordination*. This typically occurs in the school choice/housing market case, especially when a household searches for a house and a school simultaneously.

Hayashi and Lombardi (2017) provides a theoretical characterization of the social outcomes that are viable under this institutional constraint when individuals behave strategically, particularly in the form of Nash equilibria. They consider a society with multiple sectors in which each sector authority oversees the given sector, and does not communicate with other sector authorities, and agents send their messages separately to different sector authorities.

This leaves an empirical question about the agents' behavior regarding inter-sectoral coordination under the institutional constraint. Also, it remains unclear how much allocation efficiency is indeed achieved. The current study is the first attempt to answer these questions through a controlled laboratory experiment. We achieve this by constructing a simple setting to extract the nature of the problem, which arises when several sectors use a partial equilibrium mechanism separately, based on the mis-specification described above. We focus on whether subjects can operate in an equilibrium where they report the corresponding marginal rankings induced by their true preferences for each sector, and which yield a *Pareto-dominant outcome*.

Separately running partial equilibrium mechanisms across sectors without participants communicating among themselves is rather ubiquitous. It is unclear which mechanisms we should begin our investigation with. They may be centralized or decentralized, depending on the nature of the objects that are to be allocated. Although our substantive concerns are ultimately about real-life problems, especially in the school choice/housing market case, we need to simplify the details to focus on the inter-sectoral coordination problem.

In this study, we adopt the top-trading-cycle (TTC) mechanism (Shapley and Scarf, 1974) for our partial equilibrium exchange mechanism. Although our investigation is motivated by the school choice/housing market problem, we do not intend to copy the TTC mechanism precisely. From an analytical perspective, we adopt the TTC mechanism for two reasons. First, it simplifies the laboratory experiment. We do not exclude other practical partial equilibrium mechanisms, such as auction mechanisms and decentralized trading mechanisms such as bargaining, matching, and searching. Second, the TTC mechanism has desirable benchmark properties. When it is run for a single sector, it is strategy-proof (reporting true preference is always a dominant strategy) and Pareto-efficient. It is also group strategy-proof (no group can gain by joint misreporting) and delivers a unique core allocation.

The simple nature of the TTC mechanism allows us to concentrate on the inter-sectoral coordination issue because there is no theoretical source of inefficiency or manipulation at the single-sector level. In general, other mechanisms are not fully strategy-proof or involve coordi-

Table 1: Sector 1 and Sector 2 games

(a) Sector 1 Game

A \ B	$e_{A1} \succ e_{B1}$	$e_{B1} \succ e_{A1}$
$e_{A1} \succ e_{B1}$	(e_{A1}, e_{B1})	(e_{A1}, e_{B1})
$e_{B1} \succ e_{A1}$	(e_{B1}, e_{A1})	(e_{A1}, e_{B1})

(b) Sector 2 Game

A \ B	$e_{A2} \succ e_{B2}$	$e_{B2} \succ e_{A2}$
$e_{A2} \succ e_{B2}$	(e_{A2}, e_{B2})	(e_{A2}, e_{B2})
$e_{B2} \succ e_{A2}$	(e_{B2}, e_{A2})	(e_{A2}, e_{B2})

nation problems implementing efficient allocations, even when confined to a single sector.

When TTC is run for different sectors separately, however, it is not strategy-proof overall. This makes efficiency harder to achieve. For example, consider two sectors. In both sectors, every subject is endowed with one indivisible item, as in Shapley and Scarf (1974). The TTC mechanism in Sector $i \in \{1, 2\}$ works as each subject submits a ranking for the items in Sector i. Thus, the allocation of Sector i items is determined by reported rankings for Sector i items.

However, each subject's reward is determined by the *combination* of items he or she obtained in Sectors 1 and 2. We set rewards so that the subjects mutually gain only when they successfully coordinate their reports *across* sectors to obtain particular combinations of Sector 1 and Sector 2 items. They are unable to communicate before submitting their rankings.

To demonstrate further, consider the simplest case with two subjects, A and B. A is endowed with items e_{A1} and e_{A2}, while B is endowed with items e_{B1} and e_{B2}. If we look at Sector 1 alone, each subject submits a ranking over the two items, and exchange occurs only when they place each other's items on top. The game form is summarized in panel (a) of Table 1. We can see that if preference over Sector 1 is independent of the allocation in Sector 2, it is always a dominant strategy to report the true ranking. In other words, one can never gain by misreporting his/her ranking.

Likewise, if we look at Sector 2 alone, each subject submits a ranking over the two items, and exchange occurs only when they put each other's items on top. The game form is summarized in panel (b) of Table 1. Again, we can see that if the preference over Sector 2 is independent of the allocation in Sector 1, it is always a dominant strategy to report the true ranking. In other words, one can never gain by misreporting his/her ranking.

The entire game form is summarized in Table 2. There is no longer a dominant strategy when preferences for paired items cannot be separated. Let us assume that while both players strictly prefer the other's pair to their own, any mismatched pairs are worthless to them. That is, A prefers $e_{B1}e_{B2}$ over $e_{A1}e_{A2}$, and all the other allocations are equally less ideal than $e_{A1}e_{A2}$ to him. B prefers $e_{A1}e_{A2}$ over $e_{B1}e_{B2}$, and all the other allocations are equally less ideal than

Table 2: 2-sector game

		B			
		$e_{A1} \succ e_{B1}$ $e_{A2} \succ e_{B2}$	$e_{A1} \succ e_{B1}$ $e_{B2} \succ e_{A2}$	$e_{B1} \succ e_{A1}$ $e_{A2} \succ e_{B2}$	$e_{B1} \succ e_{A1}$ $e_{B2} \succ e_{A2}$
A	$e_{A1} \succ e_{B1}$ $e_{A2} \succ e_{B2}$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$
	$e_{A1} \succ e_{B1}$ $e_{B2} \succ e_{A2}$	$(e_{A1}e_{B2}, e_{B1}e_{A2})$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$	$(e_{A1}e_{B2}, e_{B1}e_{A2})$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$
	$e_{B1} \succ e_{A1}$ $e_{A2} \succ e_{B2}$	$(e_{B1}e_{A2}, e_{A1}e_{B2})$	$(e_{B1}e_{A2}, e_{A1}e_{B2})$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$
	$e_{B1} \succ e_{A1}$ $e_{B2} \succ e_{A2}$	$(\mathbf{e_{B1}e_{B2}, e_{A1}e_{A2}})$	$(e_{B1}e_{A2}, e_{A1}e_{B2})$	$(e_{A1}e_{B2}, e_{B1}e_{A2})$	$(e_{A1}e_{A2}, e_{B1}e_{B2})$

$e_{B1}e_{B2}$ for her. The efficient allocation $(e_{B1}e_{B2}, e_{A1}e_{A2})$ can be obtained in Nash equilibrium, but it occurs only when A and B successfully coordinate their reports in both sectors. Note that it is optimal for A to submit the ranking $e_{B1} \succ e_{A1}$ in Sector 1 *because* he is expecting to get e_{B2} instead of e_{A2} in Sector 2, and it is optimal for him to rank $e_{B2} \succ e_{A2}$ in Sector 2 *because* he is expecting to get e_{B1} instead of e_{A1} in Sector 1. A similar circularity occurs for B as well. In other words, these "rankings" are equilibrium constructs.

The efficient allocation above is a Pareto-dominant outcome, however, it is somewhat risky to achieve because a single failure in either sector leads to an allocation with unmatched pairs, which is the worst case. This is riskier when there are more than two subjects involved in these exchanges. This leaves the possibility that the subjects send messages so that no trade occurs in either sector, which is Pareto-inferior but a "safe" second-best. For example, because trade occurs only by mutual agreement, no trade is always a trivial equilibrium.

Our research questions are as follows: (i) *are subjects able or willing to engage in coordination across sectors to obtain an efficient allocation in the presence of complementarity when partial equilibrium mechanisms are run separately?*; (ii) *quantitatively, what is the success rate and loss of efficiency?* Furthermore, we ask (iii) *by how much does sequentially running the mechanisms across sectors help the subjects improve their inter-sectoral coordination* compared with simultaneously running the mechanisms.

We consider five games played by three subjects. Games 1 and 2 have only a single sector, and they serve as our benchmark. Game 1 is the simplest, in the sense that the TTC mechanism finalizes allocation in one round.

Game 2 is more complex so that the mechanism finishes in two rounds after one subject leaves in the first round.

Games 3, 4, and 5 have two sectors. Games 3 and 4 have complementarity between sectors, but Game 5 does not have inter-sectoral complementarity. Game 3 is simpler in the sense that the trading cycles required for the first-best allocation exhibit the same pattern across two sectors, so that the inter-sectoral coordination is straightforward. Game 4 is more complex because the first-best allocation requires opposite directions of trading cycles across sectors. Hence, the inter-sectoral coordination is less straightforward in Game 4. There is no need for inter-sectoral coordination in Game 5 because the two sectors are independent. There are two treatments: one in which the two-sector games (Games 3,4, and 5) are run *simultaneously* and the other in which they are run *sequentially*.

We find that when two sectors are lined up in a simpler way (Game 3), the problem of inter-sectoral coordination is minor. Participants achieve an efficiency level like that in the single-sector problem, despite the need for inter-sectoral coordination. Sequential elicitationdoes not improve upon the high efficiency of simultaneous elicitation. However, when two sectors are lined up in more complex ways (Games 4 and 5), efficiency falls compared with the single-sector case. Surprisingly, this applies even in the absence of inter-sectoral coordination (Game 5), and in such a case, sequential elicitation improves efficiency, compared with simultaneous elicitation.

The remainder of this paper is organized as follows: Section 2 provides a summary of the literature that is most relevant to our work. The details of the experimental design are presented in Section 3. Section 4 presents the results, and Section 5 provides concluding remarks.

2 Related Literature

To our knowledge, the current paper is the first experimental approach to the intersectoral coordination problem, in the context of social choice and implementation. It is motivated by the theoretical work of Hayashi and Lombardi (2017), which is a natural extension of the Nash-implementation problem (Maskin, 1999) in a multisectoral environment where the sectors do not communicate with each other. Cabrales et al. (2003) performed an experiment on Maskin's canonical mechanism for Nash implementation, in a single-sector environment with three people and three abstract outcomes, and found that the mechanism successfully implements the desired outcome in a large majority of instances. It is left unclear, however, whether we can achieve a desired outcome under the institutional constraint in which we must run mechanisms separately for different sectors despite the existence of complementarity between the sectors.

Our sequential treatment is motivated by the theoretical work of Hayashi and Lombardi (2019), which studies what can be implemented in the multi-period setting in which allocation in the current period must be chosen and finalized, without any commitment to allocations in future periods. This handles more restricted situations than in the existing research on subgame-perfect implementation (Moore and Repullo, 1988), which allows that an entire social outcome, once chosen at some stage, can be overturned at any subsequent stage. Some obstacles for subgame-perfect implementation are reported. Aghion et al. (2018) find that the Moore and Repullo mechanism does not induce truth-telling as theoretically predicted and that individuals lie because of pessimistic beliefs about subsequent players' rationality. Fehr et al. (2021) find that sequential mechanisms induce an individual to retaliate against somebody who chose, in a previous stage, something socially desirable but unfavorable at a previous stage. In our experiment, on the other hand, sequential treatment improves efficiency over simultaneous treatment. This is because the allocation of Sector 1 items is finalized at Stage 1, and this makes it more straightforward to understand how to play in Stage 2, which in turn makes playing in Stage 1 more straightforward.

Another related problem is the auction of multiple items, where the bidders' preferences are for complementary bundles, and the question is whether it is better for the seller to bundle the items or not (see, Avery and Hendershott, 2000; Krishna and Rosenthal, 1996; Levin, 1997; Subramaniam and Venkatesh, 2009). Popkowski Leszczyc and Häubl (2010) experimentally show that bundling items promotes aggressive bids by the bidders with a preference for complementary bundles when the degrees of complementarity are known. However, the theoretical works above show that there is a range of environments in which it is beneficial for the seller to run separate auctions for different items. This is primarily because the necessity of winning all the items makes certain bidders aggressive in each auction when they are unsure about the degrees of complementarity for the other bidders. Such situations generate a positive probability of inefficiency, in the sense that a bidder with a preference for complementarity can win only some items, which is worthless to the bidder, and thus he has to resell. This point relates to the nature of efficiency loss in our problem.

Although our choice of the TTC mechanism is only meant to be a simplified expression of general situations in which partial equilibrium mechanisms are being operated, there are actual instances of allocation problems where this mechanism is applicable, at least at an experimental level, and some cases are put into practice. In addition, one may have a legitimate question about whether the TTC mechanism works in the single-sector case.

Abdulkadiroğlu and Sönmez (2003) extends the TTC and Gale–Shapley (GS) mechanisms to the school choice problem, and shows that they are strategy-proof, in that, it is always a dominant strategy for each student to submit his/her true preference, in contrast to the traditional Boston mechanism. They also show that the TTC mechanism achieves efficiency among students, although, unlike the GS mechanism, it does not eliminate justifiable envy between students.

Chen and Sönmez (2006) conducts an experimental study of school choice and reports that the TTC and GS mechanisms improve efficiency over the Boston mechanism. Pais and Pintér (2008) experimentally shows that the TTC mechanism performs better than GS and Boston mechanisms, which is consistent with the theory, and also that TTC outperforms the other two in terms of the truthful revelation of preference and is also more robust to deviations. In a complete information setting, Chen et al. (2016) experimentally shows that the TTC mechanism outperforms the GS and Boston mechanisms in efficiency. The school choice version of the TTC mechanism has been put to practice, for example, in the New Orleans Recovery School District (see, Abdulkadiroglu et al., 2017).

Abdulkadiroğlu and Sönmez (1999) extends the TTC mechanism to the house allocation problem with existing tenants. Chen and Sönmez (2002) experimentally shows that the TTC mechanism produces significantly more efficient allocations than the random serial dictatorship mechanism, a mechanism widely used in on-campus university housing allocation.

The TTC mechanism was extended to the kidney exchange program, a rather unexpected direction, by Roth et al. (2004), so that patients can swap their living donors for a better match in blood types. The extended TTC mechanism, called top trading cycles and chains, has been put to practice in the United States (see Roth et al., 2005).

In these applications, preferences for schools and houses and the supply of living donors are considered exogenous. Our study will serve as an indicator of what we should expect when these elements are affected by a potential source of endogeneity due to complementarity with allocations in other sectors.

In the two-sector games in our study, there is a Nash equilibrium that achieves the first-best although there is generally no dominant strategy. This is reminiscent of the theoretical observation that the Boston mechanism is not strategy-proof, but implements efficient outcomes in Nash equilibria (Ergin and Sönmez, 2006). In a school choice experiment, Featherstone and Niederle (2016) shows that the efficiency level achieved by such a non-strategy-proof mechanism is not high. Our results under simultaneous elicitation when two sectors are asymmetric aligns with their results.

3 Experimental Design and Procedure

3.1 Games

Each experiment consisted of five games, two of which consisted of only one sector (as a benchmark), while the remaining three consisted of two sectors each. Each game was played by three subjects, so that the coordination problem, as described in the example of the previous section, with two players would be less obvious.

The five games are summarized in Tables 3 and 4. $\pi_i(\cdot)$s in Table 4, represents the payoff that player i obtains when he receives none of the three pairs above it. Those shown in bold are the first-best equilibrium allocations and payoffs.

Games 1 and 2: The one-sector top-trading-cycle mechanism

The purpose of running the two one-sector games was to establish the behavioral benchmark of the TTC mechanism.

Each of the three subjects received an initial item and a list of monetary evaluations for the three items. The reward is determined by the value of the item he/she receives as the final allocation.

Subjects simultaneously submitted their rankings for the three items. See Figure B.1 in Online Supplementary Material for a screenshot of this. The final allocation of the three items is determined according to the TTC mechanism based on the submitted rankings.

Given a list of submitted rankings, the TTC mechanism works as follows. The text below seems to describe a dynamic process. However, this is just an illustration of the algorithm to determine the outcome. The game itself is static.

Definition 1 Top-trading-cycle (TTC) mechanism

Step 1. Each agent indicates the owner of their favorite item. There is at least one cycle (including a self-cycle) because there are finite agents. Each agent in a cycle is removed from the market with the assigned item that they indicate. If there is at least one remaining agent, proceed to the next step.

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Step k. Each remaining agent points to the owner of their favorite item. There is at least one cycle (including a self-cycle). Give each agent in a cycle the item they indicate and remove

Table 3: one-sector games (Games 1 and 2)

Game 1

A	B	C
$\pi_{\mathbf{A}}(\mathbf{e_C}) = \mathbf{24}$	$\pi_{\mathbf{B}}(\mathbf{e_A}) = \mathbf{24}$	$\pi_{\mathbf{C}}(\mathbf{e_B}) = \mathbf{24}$
$\pi_A(e_B) = 12$	$\pi_B(e_C) = 12$	$\pi_C(e_A) = 12$
$\pi_A(e_A) = 6$	$\pi_B(e_B) = 6$	$\pi_C(e_C) = 6$

Game 2

A	B	C
$\pi_{\mathbf{A}}(\mathbf{e_A}) = \mathbf{24}$	$\pi_B(e_A) = 24$	$\pi_C(e_A) = 24$
$\pi_A(e_B) = 12$	$\pi_{\mathbf{B}}(\mathbf{e_C}) = \mathbf{12}$	$\pi_{\mathbf{C}}(\mathbf{e_B}) = \mathbf{12}$
$\pi_A(e_C) = 6$	$\pi_B(e_B) = 6$	$\pi_C(e_C) = 6$

Table 4: two-sector games (Games 3 to 5)

Game 3

A	B	C
$\pi_{\mathbf{A}}(\mathbf{e^1_C}, \mathbf{e^2_C}) = \mathbf{24}$	$\pi_{\mathbf{B}}(\mathbf{e^1_A}, \mathbf{e^2_A}) = \mathbf{24}$	$\pi_{\mathbf{C}}(\mathbf{e^1_B}, \mathbf{e^2_B}) = \mathbf{24}$
$\pi_A(e^1_B, e^2_B) = 18$	$\pi_B(e^1_C, e^2_C) = 18$	$\pi_C(e^1_A, e^2_A) = 18$
$\pi_A(e^1_A, e^2_A) = 12$	$\pi_B(e^1_B, e^2_B) = 12$	$\pi_C(e^1_C, e^2_C) = 12$
$\pi_A(\cdot) = 6$	$\pi_B(\cdot) = 6$	$\pi_C(\cdot) = 6$

Game 4

A	B	C
$\pi_{\mathbf{A}}(\mathbf{e^1_C}, \mathbf{e^2_B}) = \mathbf{24}$	$\pi_{\mathbf{B}}(\mathbf{e^1_A}, \mathbf{e^2_C}) = \mathbf{24}$	$\pi_{\mathbf{C}}(\mathbf{e^1_B}, \mathbf{e^2_A}) = \mathbf{24}$
$\pi_A(e^1_B, e^2_C) = 18$	$\pi_B(e^1_C, e^2_A) = 18$	$\pi_C(e^1_A, e^2_B) = 18$
$\pi_A(e^1_A, e^2_A) = 12$	$\pi_B(e^1_B, e^2_B) = 12$	$\pi_C(e^1_C, e^2_C) = 12$
$\pi_A(\cdot) = 6$	$\pi_B(\cdot) = 6$	$\pi_C(\cdot) = 6$

Game 5

A	B	C
$\pi_A(e^1_A, e^2_B) = 24$	$\pi_B(e^1_A, e^2_B) = 24$	$\pi_C(e^1_A, e^2_B) = 24$
$\pi_{\mathbf{A}}(\mathbf{e^1_A}, \mathbf{e^2_C}) = \pi_A(e^1_B, e^2_B) = \mathbf{18}$	$\pi_B(e^1_A, e^2_C) = \pi_{\mathbf{B}}(\mathbf{e^1_C}, \mathbf{e^2_B}) = \mathbf{18}$	$\pi_C(e^1_A, e^2_A) = \pi_C(e^1_B, e^2_B) = 18$
$\pi_A(e^1_A, e^2_A) = \pi_A(e^1_C, e^2_B) = 15$	$\pi_B(e^1_A, e^2_A) = \pi_B(e^1_B, e^2_B) = 15$	$\pi_C(e^1_A, e^2_C) = \pi_C(e^1_C, e^2_B) = 15$
$\pi_A(e^1_B, e^2_C) = 12$	$\pi_B(e^1_C, e^2_C) = 12$	$\pi_{\mathbf{C}}(\mathbf{e^1_B}, \mathbf{e^2_A}) = \mathbf{12}$
$\pi_A(e^1_B, e^2_A) = \pi_A(e^1_C, e^2_C) = 9$	$\pi_B(e^1_C, e^2_A) = \pi_B(e^1_B, e^2_C) = 9$	$\pi_C(e^1_B, e^2_C) = \pi_C(e^1_C, e^2_A) = 9$
$\pi_A(e^1_C, e^2_A) = 6$	$\pi_B(e^1_B, e^2_A) = 6$	$\pi_C(e^1_C, e^2_C) = 6$

Two sectors in Game 5 are separable

Sector 1

A	B	C
$\pi_{\mathbf{A}}(\mathbf{e^1_A}) = \mathbf{12}$	$\pi_B(e^1_A) = 12$	$\pi_C(e^1_A) = 12$
$\pi_A(e^1_B) = 6$	$\pi_{\mathbf{B}}(\mathbf{e^1_C}) = \mathbf{6}$	$\pi_{\mathbf{C}}(\mathbf{e^1_B}) = \mathbf{6}$
$\pi_A(e^1_C) = 3$	$\pi_B(e^1_B) = 3$	$\pi_C(e^1_C) = 3$

Sector 2

A	B	C
$\pi_A(e^2_B) = 12$	$\pi_{\mathbf{B}}(\mathbf{e^2_B}) = \mathbf{12}$	$\pi_C(e^2_B) = 12$
$\pi_{\mathbf{A}}(\mathbf{e^2_C}) = \mathbf{6}$	$\pi_B(e^2_C) = 6$	$\pi_{\mathbf{C}}(\mathbf{e^2_A}) = \mathbf{6}$
$\pi_A(e^2_A) = 3$	$\pi_B(e^2_A) = 3$	$\pi_C(e^2_C) = 3$

them from the market with their assigned item. If there is at least one remaining agent, proceed with the next step.

...

Because there are a finite number of agents, this process ends after a finite number of rounds.

In the single-sector setting, it is known that reporting the true preference is always a dominant strategy. There is a unique core allocation, and the mechanism implements the core allocation in the dominant strategy (see, Roth, 1982).

Game 1 is the simplest, and the exchange is completed in one round; hence, only the first reported item matters. Game 2 is more complicated, and the exchange requires two rounds to provide the first-best allocation; hence, more than just the item reported first matters. Thus, we hypothesize that the subjects are more likely to achieve an efficient outcome in Game 1 than with Game 2.

Games 3, 4, and 5: two-sector games

We consider three two-sector games, in which there is complementarity between the two sectors in Games 3 and 4. In the remaining Game 5, the two sectors are independent. In these games, each of the three subjects receives a *pair* of items, one for Sector 1 and the other for Sector 2, and a list of monetary evaluations of the *pairs* of items. The reward is determined by the value of the pair of items he or she receives in the final allocation.

In each sector, subjects simultaneously submit rankings for the three items. The timing of the ranking submissions *between* the two sectors differs depending on the simultaneous and sequential treatments, as we will explain later.

Game 3 is simpler because the directions of trading cycles required for the first-best allocation are the same across sectors, and thus, coordination is relatively straightforward. Game 4 is more complex, in that, the first-best allocation requires opposite trading cycle directions across sectors, and it is more difficult to obtain the first-best allocation. Thus, we expect that subjects are more likely to achieve an efficient outcome in Game 3 than in Game 4. It should also be noted that the preference orderings of the items in Sector 1 for the three best allocations for each subject in Games 3 and 4 are identical to those of Game 1. Thus, by comparing the rankings submitted in Game 1 and Sector 1 of Games 3 and 4, we can investigate the effect of having an additional sector to consider in two-sector games, compared with the one-sector game when the two sectors are not separable.

Table 5: Pareto-dominant equilibrium strategies

	Player A	Player B	Player C
Game 1	Rank e_C first	Rank e_A first	Rank e_B first
Game 2	Rank e_A first	Rank e_C above e_B	Rank e_B above e_C
Game 3	Rank e_C^1 first Rank e_C^2 first	Rank e_A^1 first Rank e_A^2 first	Rank e_B^1 first Rank e_B^2 first
Game 4	Rank e_C^1 first Rank e_B^2 first	Rank e_A^1 first Rank e_C^2 first	Rank e_B^1 first Rank e_A^2 first
Game 5	Rank e_A^1 first Rank e_C^2 above e_A^2	Rank e_C^1 above e_B^1 Rank e_B^2 first	Rank e_B^1 above e_C^1 Rank e_A^2 above e_C^2

In Game 5, the evaluation of pairs is separable across sectors, in the sense that the preference for Sector 1 items is independent of Sector 2 allocation and vice versa. In fact, each individual's total payoff is the sum of those in the two sectors. Thus, in this game, it is a dominant strategy to submit the marginal ranking in each sector, as in our two one-sector games. We aim to determine if this property is preserved under a two-sector setting. It is possible that the subjects fail to play the dominant strategy because of apparent complications related to facing two sectors that are not symmetric, even when there is no complementarity between them. Note that, considered separately, the preference ordering of Sector 1 of Game 5 for the three players is identical to that of Game 2, and, although not identical, Sector 2 has a similar structure. Thus, by comparing the efficiency of the allocation and rankings submitted by subjects between Games 2 and 5, we investigate the effect of having two sectors, in the absence of complementarity between the two sectors, on the behavior and efficiency of the mechanism. Note, however, that the bottom of Table 4 explaining this separability was *not* shown to the subjects.

There are many Nash equilibria in the above games because the TTC mechanism leaves many indifferences for a player when he is not pivotal (see Table 2 for an illustration). This is typical for mechanisms that are strategy-proof when run for a single sector. Thus, we identify the theoretical equilibria through certain refinements and compare them with the experimental data. In particular, we focus on the Pareto-dominant (PD) Nash equilibrium.[1] Table 5 summarizes the characteristics of the PD equilibrium strategies for each player in the five games.

Let us summarize the key comparisons we would like to make among these five games, considering our main research objective of understanding the behavioral consequences of constructing two separate TTC mechanisms for allocating items over two sectors when, in fact, these decisions

[1] We have also considered equilibrium in weakly dominant (WD) strategies in Games 1, 2, and 5. In Game 1, truth-telling is a unique WD strategy for each player. In Game 2, there are two WD strategies for Player A. Player A's best item is his own endowment, and he can secure his best item by selecting himself without specifying the ranking between the endowments of Players B and C. Likewise, in Game 5, Player A has two WD strategies in Sector 1, and Player B has two WD strategies in Sector 2. See Appendix B for frequencies of WD ranking submission in Games 1, 2, and 5.

should not be considered separately.

- Game 1 vs Game 2: the effect of the differences in the TTC mechanism to reach the final allocation of the subjects' behavior and efficiency.
- Game 2 vs Game 5: the effect of having two sectors, instead of one, when the two sectors are separable.
- Game 1 vs Game 3 vs Game 4: the effect of having two sectors, instead of one, when the two sectors are complementary, and the two sectors are either symmetric (Game 3) or asymmetric (Game 4).

3.2 Two treatments

We consider two treatments, simultaneous and sequential, that differ in the timing of ranking submissions in the two sectors in Games 3, 4, and 5. This choice is motivated by our interest in mechanism design. The literature of subgame-perfect implementation (following Moore and Repullo, 1988) suggests that the sequential elicitation of information helps the agents achieve coordination more effectively because it allows for more chances to adjust their information transmission across stages. There are, however, two concerns.

First, although most studies in the subgame-perfect implementation literature allow canceling at any stage, this is not a realistic assumption in the multi-sector setting. Note that when sequential elicitation is applied for the two-sector allocation problem, a realistic specification is that the allocation for one sector is finalized in the first stage, without any commitment to allocation for the other sector to be made in the second stage, and no cancellation of the first sector allocation is allowed afterwards (Hayashi and Lombardi, 2019). This is typically the case when we must finalize housing allocation before school seats are assigned. The second concern is that a sequential mechanism may motivate an agent to retaliate against others, depending on what happened in the previous stage (Fehr et al., 2021).

These concerns motivate an empirical investigation about whether sequential elicitation performs better than simultaneous one in the problem of allocation with multiple sectors, as specified.

Simultaneous treatment

In the simultaneous treatment, in Games 3, 4, and 5, subjects simultaneously submit rankings for the three items *in each sector separately.* See Figure B.3 in Online Supplementary Material for a screenshot.[2]

Sequential treatment

In the sequential treatment, Games 3, 4, and 5 consist of two stages as follows.

Stage 1: The subjects simultaneously submit rankings for the three items in Sector 1. See Figure B.5 in Online Supplementary Material for a screenshot.[3] Then, the TTC algorithm is run, and the allocation in Sector 1 is determined. The subjects were informed of both ranks and the allocation in their group in Sector 1. See Figure B.6 in Online Supplementary Material for a screenshot.

Stage 2: The subjects simultaneously rank the three items in Sector 2. See Figure B.7 in Online Supplementary Material for a screenshot. As one can see from the screenshot, the subjects are reminded of the allocation in Sector 1 when submitting their rankings for Sector 2. Then, the TTC algorithm is run and the allocation in Sector 2 is determined. The subjects were informed of the rankings and the final allocated goods for both sectors at the end. See Figure B.8 in Online Supplementary Material for a screenshot.

In each game, there is a natural subgame-perfect equilibrium path that yields the same first-best allocation, as obtained in the corresponding Nash equilibrium in the simultaneous treatment.[4] We expect that this sequential elicitation of rankings in the two sectors will facilitate our subjects following equilibrium behavior and improve their welfare.

3.3 Procedure

Our subjects played all five games during the experiment. Some simultaneous treatment sessions start with one-sector games, while others start with two-sector games. In the sequential treatment, we always started with two-sector games because our focus is on investigating the effect of sequential elicitation in two-sector games in comparison to simultaneous elicitation. The first game the subjects played differs across sessions. In half of the sessions starting with a one-sector game, the subjects played Game 1 first. In the other half, Game 2 was played first. Similarly,

[2]Note that in the experiment Sectors 1 and 2 are called Types A and B, respectively.

[3]As noted above, in the experiment, Sectors 1 and 2 are called Types A and B, respectively.

[4]Sequential implementation leaves a potential problem of manipulation, in that, one may have an incentive to manipulate the Stage 1 outcome to manipulate the Stage 2 outcome. In general, when an individual claims to demand a particular item at Stage 1, we cannot determine whether this is because she truly wants this item as an individual object or if she wants the item that follows in Stage 2 as the consequence of acquiring it. Hayashi and Lombardi (2019) show that this incentive problem restricts the class of implementable social objectives. However, this problem is excluded in our payoff setting because the first-best pair of items is PD, and nobody has an incentive to manipulate the Stage 1 outcome to manipulate that of Stage 2.

Games 3, 4, and 5 were played first in one-third of the sessions that started with two-sector games. The order of the remaining two-sector games was counterbalanced across sessions.[5]

Subjects performed each of the one-sector games thrice, and each of the two-sector games six times.[6] We call one play of a game a round. Thus, all subjects played 24 rounds (3 rounds × one-sector games + 6 rounds × two-sector games). At the beginning of each round, subjects were randomly matched into groups of three. Their roles within their group (A, B, or C)[7] are randomly reassigned once the group is created at the beginning of each round. Subjects were informed that they would play a total of 24 rounds, although the explanation of the specificity of one- or two-sector games was given only at the beginning of the relevant games. Thus, those subjects who started with one-sector games received the instructions regarding the two-sector game only after they had finished playing six rounds of one-sector games. Similarly, those subjects who started with two-sector games received instructions for the one-sector games only after they had finished playing 18 rounds of two-sector games. See Online Supplementary Material for an English translation of the instructions for our experiments.

In addition to the 1000 JPY show-up fee, subjects were paid based on the payoff they obtained in one of the 24 rounds randomly chosen at the end of the experiment. All subjects in the same session were rewarded, based on the same randomly chosen round. The points obtained in the chosen round were converted to JPY where 1 point = 100 JPY. At the end of the experiment, a set of questionnaires were used to gather the individual characteristics of our subjects.[8] The experiment lasted for an average of 100 minutes for simultaneous treatments and 110 minutes for sequential treatments.

4 Results

Experiments were conducted between May 2017 and November 2018 at the Center for Experimental Economics, Kansai University, Osaka, Japan.[9] Most of the participants were undergraduate students (the others were graduate students). They were recruited using the online billboard of Kansai University. Each participant participated in the experiment only once. There were

[5] We have implemented within-subjects design for five games and between-subjects design for two treatments. The main reason is that sequential treatment experiments followed our simultaneous experiments, as an additional treatment to respond to the comments we have received while presenting the results from simultaneous treatments.

[6] We have opted for more repetitions in two-sector games because we believed that participants needed more time to familiarize themselves with the mechanism.

[7] Called player 1, 2, or 3 in the experiment.

[8] The questionnaire included part of the advanced version of Raven's Progressive Matrix (RPM) test (Raven, 1998). We did not provide a monetary incentive for the RPM test. Appendix D emphasizes why we have conducted an RPM test and summarizes the results of analyses that utilize the RPM test score.

[9] Experiments were computerized using z-Tree (Fischbacher, 2007).

Table 6: The average total payoffs when all players uniformly randomize their ranking submission (Π^R) and the total payoffs under the equilibrium (Π^{Eq})

game	1	2	3	4	5
Π^R	32	39.5	28.125	28.125	39.5
Π^{Eq}	72	48	72	72	48

a total of 381 subjects, none of whom had participated in similar experiments.[10] Participants earned, on average, JPY 2,590, including the show-up fee.[11]

We compare (a) the extent to which participants follow equilibrium behavior and (b) the total welfare of group members. The former is measured by the average frequencies of participants submitting equilibrium rankings. For the latter, because the deviation from the equilibrium ranking submission has varying welfare consequences between games, we consider payoffs relative to the expected payoffs when players completely randomize their ranking submissions.[12] We call this measure *the relative efficiency*. In particular, the relative efficiency (RE) for group g is defined as

$$\text{RE}^g = \frac{\sum_{j \in g} \pi_j - \Pi^R}{\Pi^{Eq} - \Pi^R}$$

where π_j is the realized payoff for player j in group g, Π^R is the average total payoff (for three players) when all the players are uniformly randomizing their ranking submissions, and Π^{Eq} is the total payoff for three players under the equilibrium. Table 6 shows Π^R and Π^{Eq} for each game.

4.1 One-sector games (Games 1 and 2)

We first analyze the results from the two one-sector games. We compared outcomes between Games 1 and 2 in simultaneous treatment for inexperienced and experienced participants. Inexperienced participants played the game as their first game, and experienced participants were those who played the game last. We present the first and the last to demonstrate the effect of learning.[13]

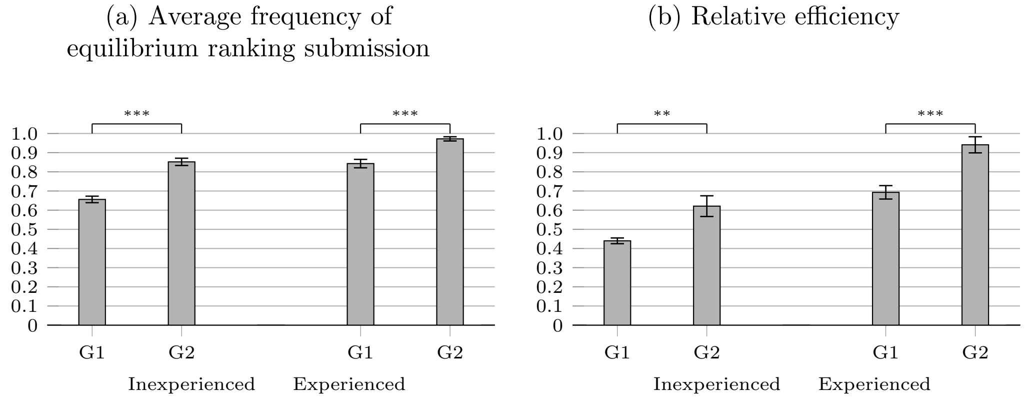
[10] Appendix A summarizes the experimental sessions. The number of participants varied between sessions because of variation in the attendance rate between sessions.

[11] JPY 100 $\approx$ USD 0.9 at the time of the experiments.

[12] We thank an anonymous referee for this suggestion.

[13] See Appendix B for the results from each ordering, that is, for participants who played the game as their first, second, fourth, and fifth game. There is a significant increase in the frequency of equilibrium ranking submission between participants who played these one-sector games before (the first or the second) or after (the fourth and the fifth) two-sector games. We do not pool the data of one-sector games from simultaneous and sequential treatments and use the data only from the simultaneous elicitation treatment. This is because, in the sequential treatment, one-sector games were always played after the two-sector games. In addition, within one-sector games, Game 1 was always played before Game 2.

Figure 1: Game 1 (G1) vs Game 2 (G2)



Note. Based on the estimated coefficient of game dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level based on the Wald test.

Panel (a) Figure 1 shows the average frequency, during three rounds of playing the game, of the subject submitting the equilibrium ranking in Game 1 (G1) and Game 2 (G2).[14] We observe that the frequency of the equilibrium ranking submission is higher for experienced than for inexperienced participants. Thus, participants learn, based on the experience of playing similar games, to submit rankings consistent with equilibrium more frequently.

Figure 1 also shows that a significantly higher frequency of equilibrium ranking submission in G2 than in G1 manifests as the higher average relative efficiency shown in panel (b) of Figure 1.[15] Thus, contrary to our expectation that the efficient outcome is more likely to be achieved in G1 than in G2, G2 resulted in higher relative efficiency. This is because, although we did not foresee this when we constructed the games, the set of PD equilibrium strategies for Players B and C is larger in G2 than in G1.

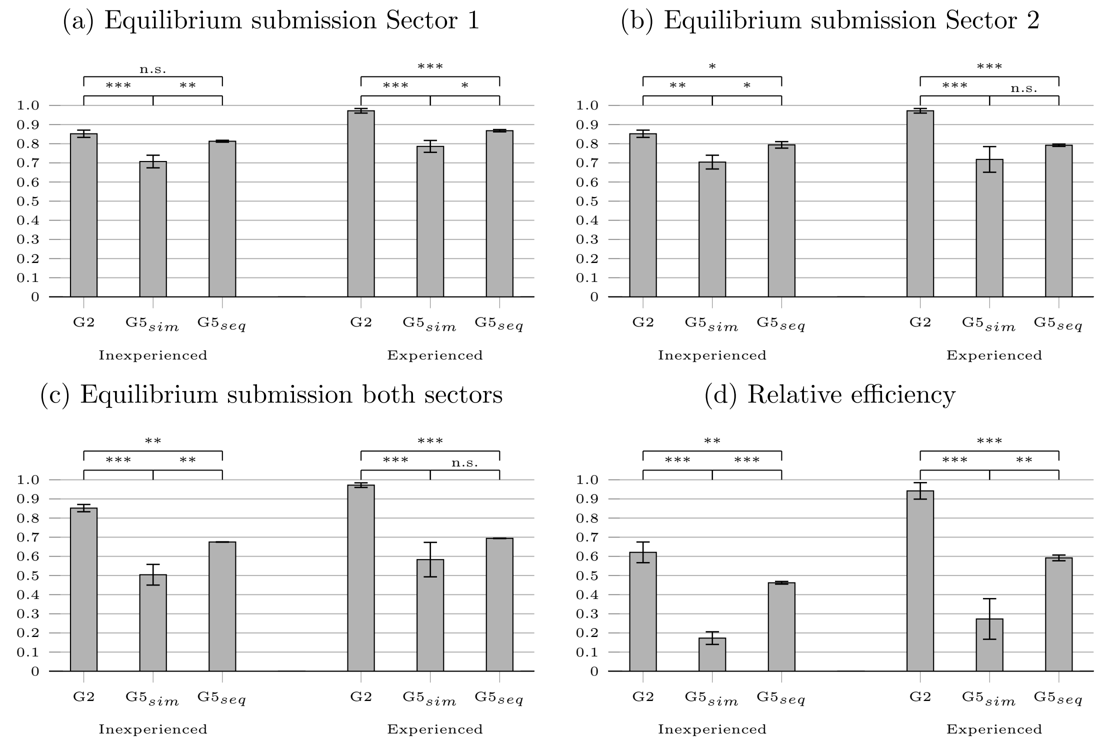
4.2 Game 2 vs Game 5

Let us now compare G2 and Game 5 (G5). We had mentioned earlier that the two sectors are separable in G5. Thus, a comparison between G2 and one of the two sectors in G5 captures the effect of complexity introduced by the mere fact of needing to consider two sectors when

[14] Because of the random regrouping of subjects after each round, the observations from subjects who participated in the same experimental sessions are not independent. We adjust for possible within-session correlations by running linear regressions and using robust standard errors that adjust for the session-clustering effect. For example, Figure 1 is generated by running the the following linear regression for each panel and each type of the subjects: $Y = \beta_1 G1 + \beta_2 G2 + \mu$, where Y is a fraction of three rounds in which a subject has submitted equilibrium rankings, G1 and G2 are the dummy variables that take the value 1 if the outcome is from subjects playing the relevant game (Games 1 and 2, respectively). Accordingly, the average frequency for equilibrium ranking submissions in Games 1 and 2, captured by the estimated coefficients β_1 and β_2, respectively. The results of these regressions are reported in Appendix C.

[15] For the average relative efficiency reported in Figure 1, we take the average of groups across three rounds (note that because of the random rematching, groups are different across rounds within a game). Because of random regrouping at the beginning of each round, we consider a group-round the unit of analysis and accommodate for the within-session-clustering effect by running a linear regression like that discussed in footnote 14.

Figure 2: Game 2 vs Game 5



Note. Based on the estimated coefficient of game dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level.

deciding the ranking, instead of one.

Figure 2 shows the results of comparing the average frequency of a PD equilibrium ranking submission in Sector 1 (panel (a)), Sector 2 (panel (b)), and both sectors combined (panel (c)) in G5, both simultaneous ($G5_{sim}$) and sequential ($G5_{seq}$) treatments, and those in G2. It also shows, in panel (d) the average relative efficiency for G2, $G5_{sim}$, and $G5_{seq}$.[16] As we have done for the comparison of G1 and G2 in each panel above, the outcomes for the inexperienced participants who played these games as their first game and for the experienced participants who played these games as their last game are shown.[17]

For inexperienced participants, the PD equilibrium ranking submission in Sector 1 is significantly less frequent in $G5_{sim}$ than in G2 and $G5_{seq}$ (panel (a)). The same is true for Sector 2 (panel (b)), as well as for considering both sectors jointly (panel (c)). When both sectors are

[16]The frequency of the equilibrium ranking submission and relative efficiency are computed based on the total plays of a game, that is, three for G2 and six for G5. The averages reported in the figure are based on the estimated coefficients obtained from running the the following linear regression for each panel and each type of the subjects: $Y = \beta_1 G2 + \beta_2 G5_{sim} + \beta_3 G5_{seq} + \mu$. The standard errors are corrected for session-clustering effects. The results of these regressions are reported in Appendix C.

[17]Note that the experienced participants considered for G5 here, in both sequential and simultaneous treatments, are those who started with two-sector games and played G5 as their third game before playing one-sector games. This restriction is required to compare simultaneous and sequential treatments because, in the sequential treatment, two-sector games were always played before the one-sector games. This remark applies to all the analyses involving two-sector games.

considered, the frequency of equilibrium ranking submissions is significantly lower in G5$_{seq}$ than in G2. This results in significantly lower efficiency in G5$_{sim}$ than in G5$_{seq}$, which results in significantly lower efficiency than in G2 (panel (d)). A similar tendency is observed for experienced participants as well, although the frequency of the PD equilibrium ranking submissions in G5$_{sim}$ and G5$_{seq}$ are no longer significantly different at the 5% level, partly because of a large variance in the outcome of G5$_{sim}$.

This suggests that the complexity introduced by simultaneously considering two sectors that are asymmetric, even when the two sectors are independent, makes it difficult for participants to follow equilibrium behavior. This is especially true when ranking two sectors simultaneously. This difficulty results in a significantly lower relative efficiency in G5$_{sim}$ than in G5$_{seq}$, both of which are significantly lower than G2, not only for inexperienced but also for experienced participants.

4.3 Comparison between Games 1, 3, and 4

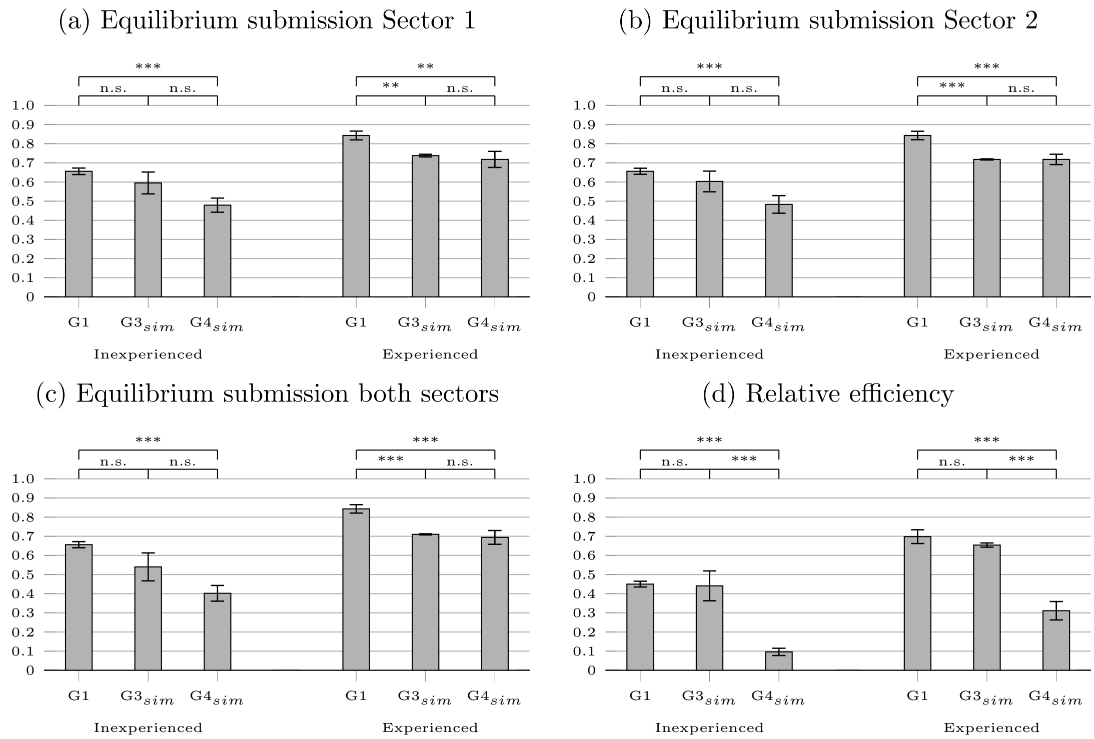
We proceed to compare the outcomes from G1, Game 3 (G3), and Game 4 (G4). Let us first consider G3 and G4 under simultaneous treatment, which will be denoted as G3$_{sim}$ and G4$_{sim}$, respectively.

Figure 3 shows the average frequencies of subjects submitting equilibrium rankings in Sector 1 (panel (a)), Sector 2 (panel (b)), and the two sectors combined (panel (c)), for both inexperienced and experienced participants. Figure 3 also reports the average relative efficiency (panel (d)). In each panel, the outcome of G1 is reported as the benchmark.[18]

Figure 3 clearly demonstrates that, as seen in the case of other games, experienced participants submit equilibrium rankings more frequently, and achieve higher efficiency, than the inexperienced participants in G3$_{sim}$ and $G4_{sim}$. It also shows that the relative efficiency achieved in G3$_{sim}$ in which two sectors are symmetric is as high as that in G1 for experienced participants (panel (d)), although the frequency of equilibrium ranking submissions is significantly different between the two (panel (c)). We also note that the asymmetry between the two sectors in $G4_{sim}$ causes a significant loss in terms of efficiency (panel (d)) compared with G3$_{sim}$, even though the frequencies of equilibrium ranking submissions in the two games are similar for experienced participants (panel (c)).

[18]The frequency of the equilibrium ranking submission and relative efficiency are computed based on the total rounds of playing a game, that is, three for G1 and six for G3 and G4. The averages reported in the figure are based on the estimated coefficients obtained from running the following linear regression for each panel and each type of the subjects: $Y = \beta_1 G1 + \beta_2 G3_{sim} + \beta_3 G3_{seq} + \beta_4 G4_{sim} + \beta_5 G4_{seq} + \mu$. The standard errors are corrected for the session-clustering effect. The results of these regressions are reported in Appendix C.

Figure 3: Game 1 vs Game 3 vs Game 4 (Simultaneous elicitation)

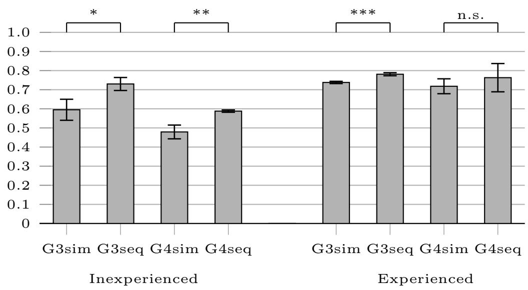


Note. Based on the estimated coefficient of game dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level.

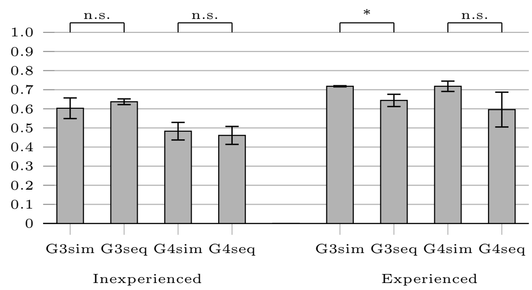
The significantly low efficiency in $G4_{sim}$ compared with G3_{sim} is a result of the higher efficiency loss in G4 compared with G3 when one or two (out of three) individuals in the group fail to submit a PD equilibrium ranking. To see this, consider the following example: Assume that Players B and C submit rankings according to the PD equilibrium in both sectors. That is, for example, Player B submits $e^s_A \succ e^s_C \succ e^s_B$ in both Sectors 1 and 2 ($s \in 1, 2$) in G3, and, in G4, $e^1_A \succ e^1_C \succ e^1_B$ in Sector 1 and $e^2_C \succ e^2_A \succ e^2_B$ in Sector 2. Imagine also that Player A deviates from the equilibrium and ranks his endowment first in both Sectors 1 and 2, which is a natural response under strategic uncertainty because it secures its own initial endowment pair. As a result, Player A obtains his own endowment and receives a payoff of 12 in G3 and G4. However, the impact of this deviation by Player A on the two remaining players differs significantly between G3 and G4. In G3, on the one hand, Player B obtains her second-most-preferred pair with the associated payoff of 18, and Player C obtains the most preferred pair with an associated payoff of 24. This results in a relative efficiency of 0.590. In G4, on the other hand, Players B and C end up exchanging their endowments in both sectors, and both obtain a payoff of 6, which is worse than securing their own endowment pairs. This results in a relative efficiency of -0.094. Indeed, in most of the cases where only one player of the group fails

Figure 4: Simultaneous vs sequential treatment: Game 3, Game 4

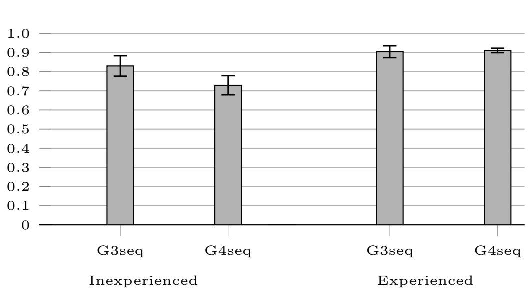
(a) Equilibrium ranking submission Sector 1



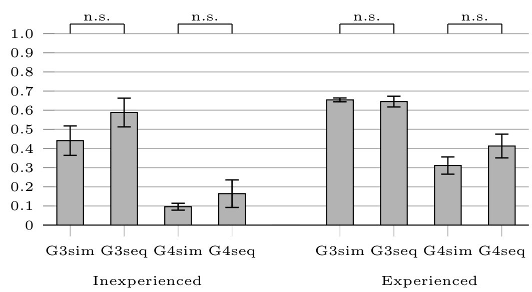
(b) Equilibrium ranking submission Sector 2



(c) Conditionally optimal ranking in Sector 2



(d) Relative efficiency



Note. Based on the estimated coefficient of game dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level.

to submit the equilibrium ranking in both sectors, the achieved relative efficiency is the same as that under this example in both games. Furthermore, in 24 out of 44 cases in which only one player in the group failed to submit the equilibrium ranking among experienced players in G4, the participant deviating from the equilibrium strategy ranked their own endowment first in both sectors, as in the above example.

Considering the comparison of G2 and G5 discussed above, as well as the comparison between G1, G3, and G4, it is suggested that the asymmetry between the two sectors results in a large efficiency loss regardless of whether complementarity exists between the two sectors. In other words, an “escape” to secure one’s initial endowment pair has a more significant impact on efficiency loss when efficient exchanges are required to occur asymmetrically across sectors.

Does sequential elicitation improve efficiency compared with simultaneous elicitation when complementarity exists between the two sectors? Unfortunately, the answer is no for both inexperienced and experienced participants. Note, however, that although the relative efficiency in the sequential treatment is not statistically significantly different from that in the simultaneous treatment (see panel (d) of Figure 4), we do observe that inexperienced participants are significantly more likely to submit equilibrium ranking in Sector 1 in the sequential treatment than in the simultaneous treatment (see panel (a) of Figure 4).

The low relative efficiency of $G4_{seq}$ compared with $G3_{seq}$ can be understood through the same example we have discussed above, to understand the low relative efficiency of $G4_{sim}$ compared with $G3_{sim}$. As shown in the above example, even when it is only one player who deviates from submitting the equilibrium marginal ranking in Sector 1, if the player ranks his own endowment first, the remaining two players who have submitted the equilibrium marginal ranking cannot perform much better after the allocation of Sector 1. Indeed, out of 36 cases where only one player in the group failed to submit the equilibrium ranking in Sector 1, 19 ranked their own endowment first.

5 Concluding Remarks

This study is the first attempt to construct a simple lab experiment that allows us to test the performance of partial equilibrium mechanisms when operated under realistic institutional constraints. Within these constraints, mechanisms are run separately with the presumption that agents' preferences are separable across sectors when, in fact, they are not. The experimental setting allows us to quantify how much we lose by operating partial equilibrium mechanisms with such a false presumption of separability. We conducted experiments in which the agents needed to coordinate their plays across sectors to obtain the first-best allocation overall.

We find that, even in the simple setting considered in our experiment, complexities introduced by a need to consider two sectors simultaneously is indeed a significant burden when the two sectors are asymmetric, and the mechanisms are run simultaneously. Surprisingly, this is true even when the two sectors are independent, and thus, there is no need for inter-sectoral coordination. Note that such a welfare loss is not observed when the two sectors are symmetric, even in the presence of complementarity. We also find that running the mechanisms sequentially can ease this burden and can reduce welfare loss. This will provide us with a lesson about when we should be careful using partial equilibrium mechanisms.

We conclude by listing suggestions for future research. In this paper, we considered a simple case of two sectors and three agents, which turned out to be already difficult to work with. This results in a question about whether inter-sectoral coordination becomes harder or easier in a larger economy with more sectors and agents. While we adopted the TTC mechanism in this study because it is one of the simplest mechanisms to work with, it is worth considering how other partial equilibrium mechanisms work. In addition, we have assumed that the degree of complementarity across sectors is homogeneous among subjects. However, there often is heterogeneity in the degree of complementarity among agents because it is vital for somebody to win both items of a particular pair, while it is not so for others. Thus, we will need to consider a more general setting than the current one in which all the subjects use the mechanisms in a symmetric manner. Finally, note that in the current study, we have restricted our attention to evaluating the performance of partial equilibrium mechanisms when they are operated under inter-sectoral complementarities, rather than identifying a behavioral cause in inter-sectoral coordination and its comparative nature across various parameters, which will naturally be of interest.

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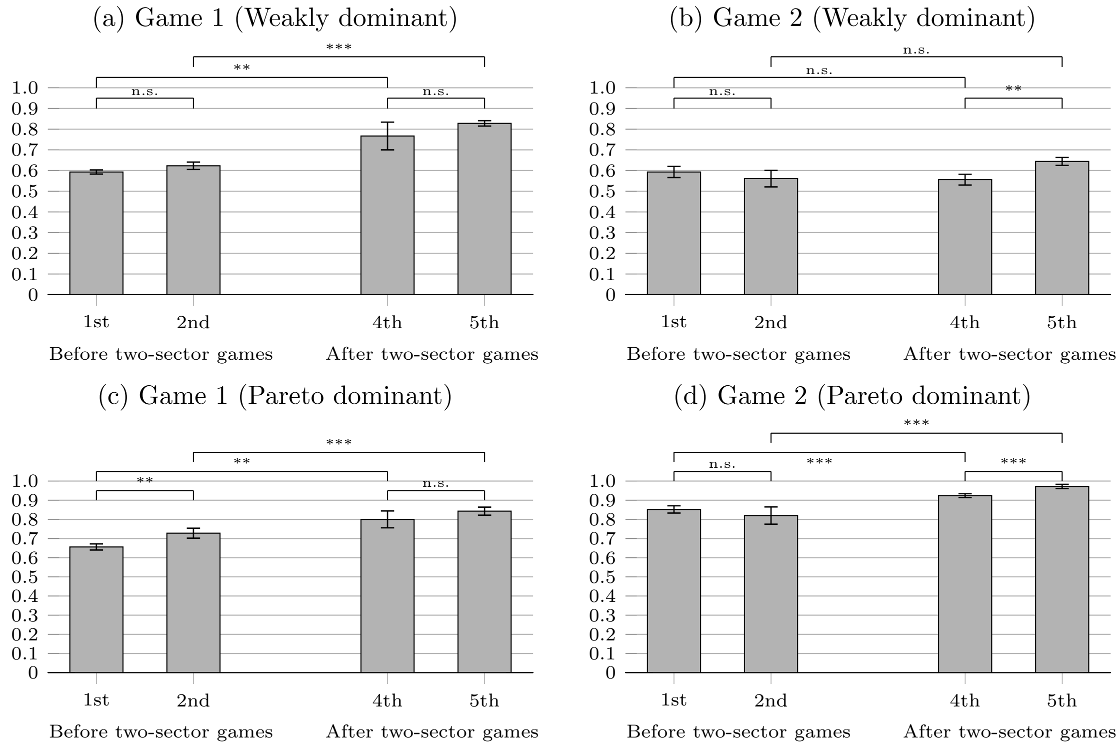
A Summary of experimental sessions

Type of Experiment	Session ID	Order of Games	Number of subjects	Average Earning (JPY)
Simultaneous	1	G1, G2, G3, G4, G5	24	2,363
Simultaneous	2	G2, G1, G3, G5, G4	15	2,320
Simultaneous	3	G4, G3, G5, G1, G2	18	2,567
Simultaneous	4	G5, G4, G3, G2, G1	21	2,571
Simultaneous	5	G1, G2, G4, G3, G5	21	2,400
Simultaneous	6	G5, G3, G4, G2, G1	24	2,525
Simultaneous	7	G3, G4, G5, G1, G2	24	2,600
Simultaneous	8	G3, G5, G4, G1, G2	18	2,700
Simultaneous	9	G4, G5, G3, G2, G1	21	2,414
Simultaneous	10	G2, G1, G4, G5, G3	18	2,400
Simultaneous	11	G1, G2, G5, G4, G3	18	2,467
Simultaneous	12	G2, G1, G5, G3, G4	21	3,413
Sequential	13	G5, G3, G4, G1, G2	24	2,850
Sequential	14	G4, G3, G5, G1, G2	24	2,700
Sequential	15	G4, G5, G3, G1, G2	27	2,600
Sequential	16	G5, G4, G3, G1, G2	18	2,533
Sequential	17	G3, G4, G5, G1, G2	24	2,600
Sequential	18	G3, G5, G4, G1, G2	21	2,600

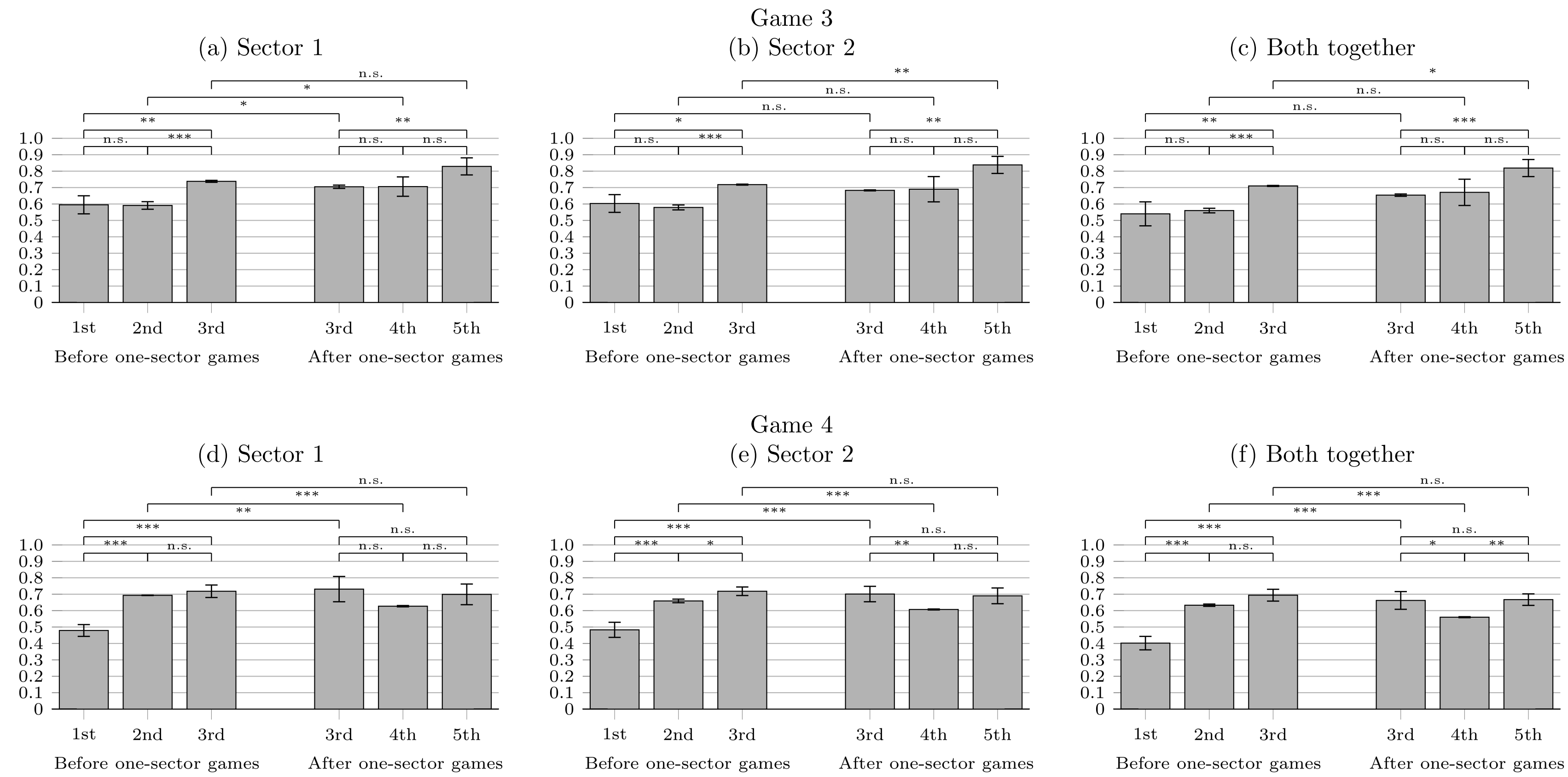
B Dynamics

Figure B.1: Average frequency of equilibrium ranking submission across ordering for one-sector games in simultaneous treatment



Note. Based on the estimated coefficient of order dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level based on the Wald test.

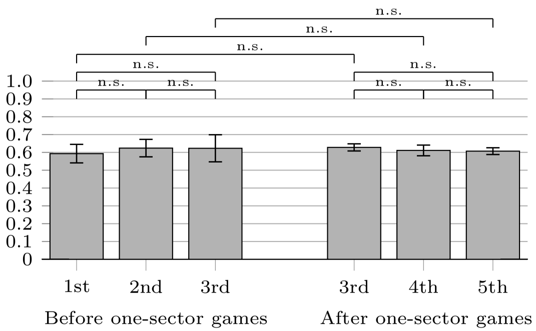
Figure B.2: Average frequency of Pareto-dominant equilibrium ranking submission across ordering in simultaneous treatment: Game 3 and Game 4



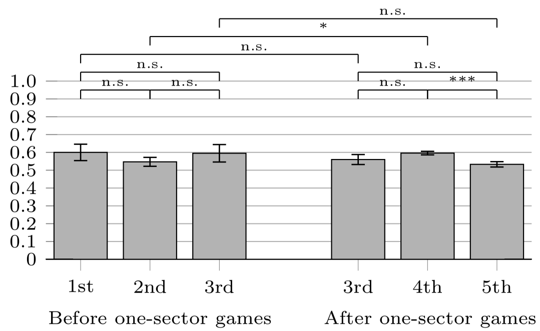
Note. Based on the estimated coefficient of order dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level based on the Wald test.

Figure B.3: Average frequency of equilibrium ranking submission across ordering in simultaneous treatment: Game 5

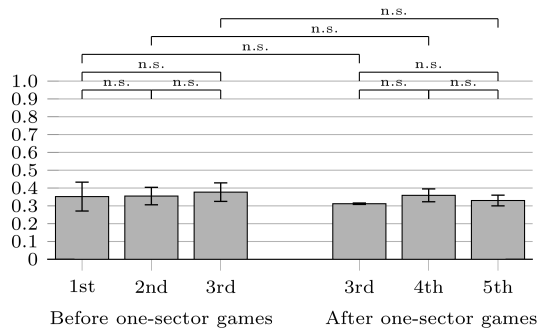
(a) Sector 1 (Weakly dominant)



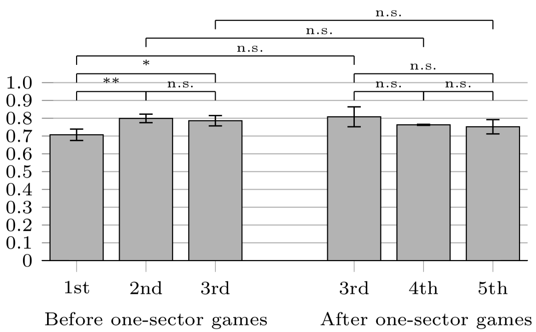
(b) Sector 2 (Weakly dominant)



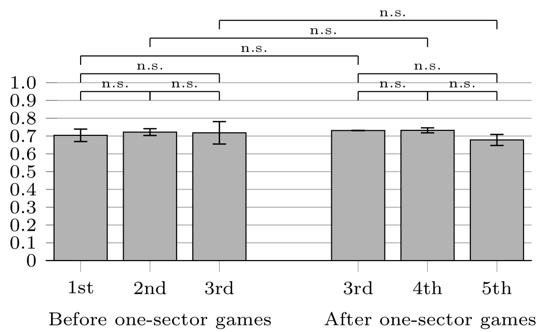
(c) Both together (Weakly dominant)



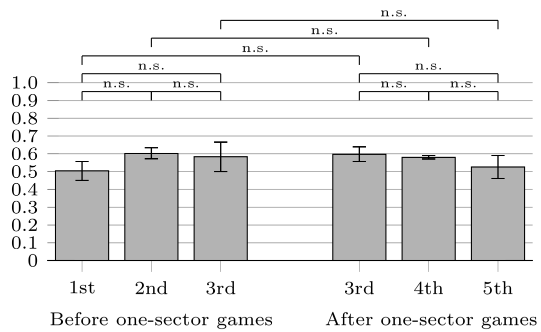
(d) Sector 1 (Pareto dominant)



(e) Sector 2 (Pareto dominant)



(f) Both together (Pareto dominant)

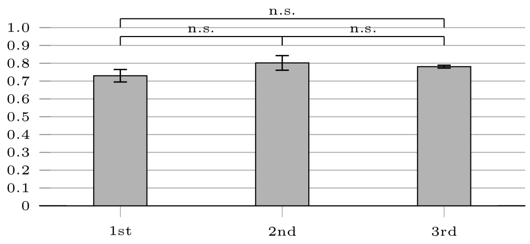


Note. Based on the estimated coefficient of order dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level based on the Wald test.

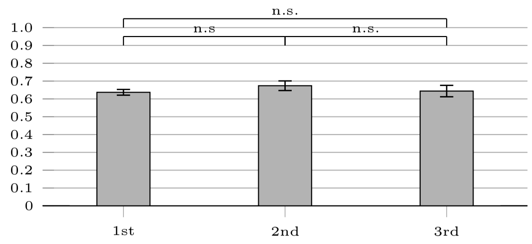
Figure B.4: Average frequency of Pareto-dominant equilibrium ranking submission across ordering in sequential treatment: Game 3 and Game 4

Game 3

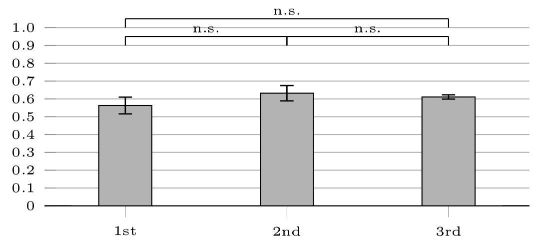
(a) Sector 1



(b) Sector 2

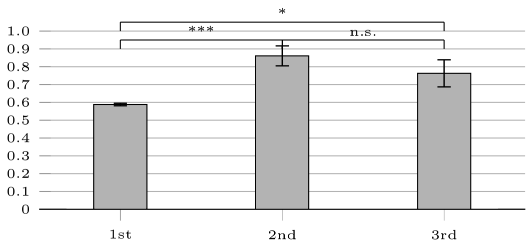


(c) Both together

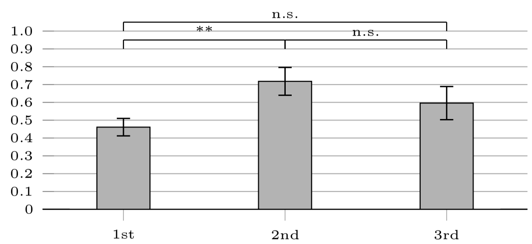


Game 4

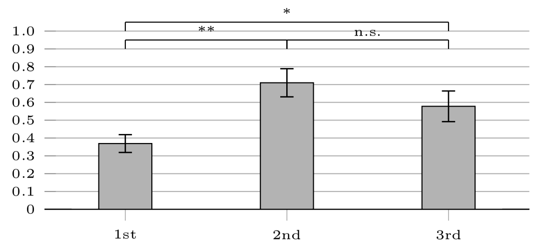
(c) Sector 1



(d) Sector 2



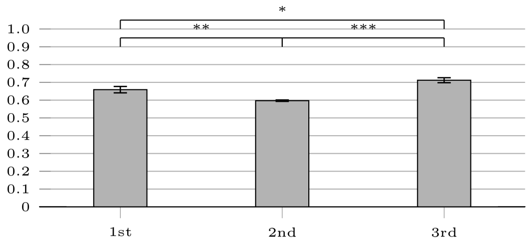
(e) Both together



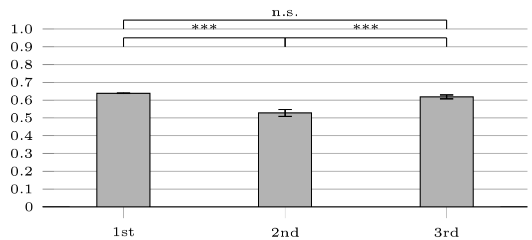
Note. Based on the estimated coefficient of order dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level based on the Wald test.

Figure B.5: Average frequency of equilibrium ranking submission across ordering in sequential treatment: Game 5

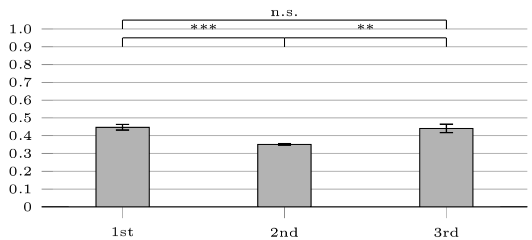
(a) Sector 1 (Weakly dominant)



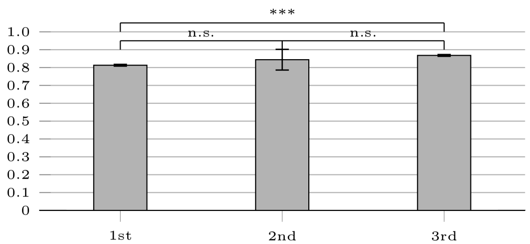
(b) Sector 2 (Weakly dominant)



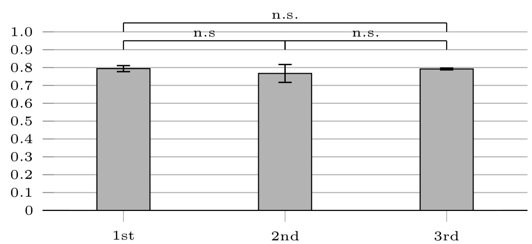
(c) Both together (Weakly dominant)



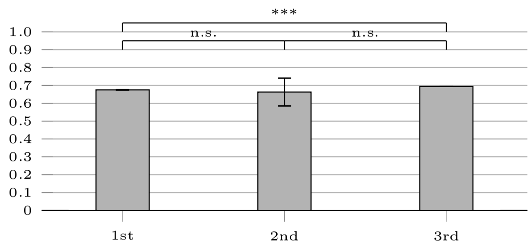
(d) Sector 1 (Pareto dominant)



(e) Sector 2 (Pareto dominant)



(f) Both together (Pareto dominant)



Note. Based on the estimated coefficient of order dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level based on the Wald test.

C Regression results

Table C.1: Regressions corresponding to Figure 1

	Pareto dominant		Relative efficiency	
	Inexp.	Exp.	Inexp.	Exp.
G1	0.656***	0.843***	0.440***	0.693***
	(0.017)	(0.022)	(0.015)	(0.035)
G2	0.852***	0.972***	0.621***	0.941***
	(0.020)	(0.011)	(0.054)	(0.042)
N	117	126	117	126
R^2	0.88	0.94	0.52	0.86
Hypothesis testing$^+$				
G1 = G2	0.0003	0.0035	0.0242	0.0060

Standard errors (adjusted for session-clustering effect) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

$^+$ p-values based on the Wald test are reported

Table C.2: Regression corresponding to Figure 2

	Sector 1		Sector 2		Both sectors		Relative Efficiency	
	Inexp.	Exp.	Inexp.	Exp.	Inexp.	Exp.	Inexp.	Exp.
G2	0.852***	0.972***	0.852***	0.972***	0.852***	0.972***	0.621***	0.941***
	(0.0193)	(0.0117)	(0.0193)	(0.0117)	(0.0193)	(0.0117)	(0.0536)	(0.0428)
$G5_{sim}$	0.707***	0.786***	0.704***	0.718***	0.504***	0.583***	0.173***	0.273***
	(0.0334)	(0.0307)	(0.0361)	(0.0668)	(0.0543)	(0.0884)	(0.0329)	(0.1057)
$G5_{seq}$	0.813***	0.868***	0.794***	0.792***	0.675***	0.694***	0.462***	0.592***
	(0.00523)	(0.00553)	(0.0166)	(0.00553)	(0.000872)	(1.24e-09)	(0.0074)	(0.0146)
N	141	150	141	150	141	150	228	240
R^2	0.93	0.96	0.95	0.80	0.91	0.92	0.40	0.67
Hypothesis testing+								
$G2 = G5_{sim} = G5_{seq}$	0.0269	0.0000	0.0260	0.6804	0.0002	0.0000	0.0003	0.0000
$G2 = G5_{sim}$	0.0096	0.0007	0.0111	0.6904	0.0009	0.0074	0.0004	0.0005
$G2 = G5_{seq}$	0.1029	0.0013	0.0619	0.7778	0.0001	0.0000	0.0262	0.0015
$G5_{sim} = G5_{seq}$	0.0202	0.0575	0.0641	0.4853	0.0199	0.2733	0.0001	0.0405

Standard errors (adjusted for session-clustering effect) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

+ p-values based on the Wald test are reported

Table C.3: Regression corresponding to Figures 3 and 4

	Sector 1		Sector 2		Both sectors		Relative Efficiency		Conditional Optimality	
	Inexp.	Exp.	Inexp.	Exp.	Inexp.	Exp.	Inexp.	Exp.	Inexp.	Exp.
G1	0.656***	0.843***	0.656***	0.843***	0.656***	0.843***	0.440***	0.693***		
	(0.0163)	(0.0215)	(0.0163)	(0.0215)	(0.0163)	(0.0215)	(0.0146)	(0.0337)		
$G3_{sim}$	0.595***	0.738***	0.603***	0.718***	0.540***	0.710***	0.442***	0.655***	0.643***	0.750***
	(0.0551)	(0.0061)	(0.0543)	(0.0030)	(0.0729)	(0.0030)	(0.0752)	(0.0099)	(0.0510)	(0.0151)
$G3_{seq}$	0.730***	0.781***	0.637***	0.644***	0.563***	0.611***	0.588***	0.646***	0.830***	0.904***
	(0.0336)	(0.0079)	(0.0151)	(0.0316)	(0.0447)	(0.0113)	(0.0735)	(0.0282)	(0.0535)	(0.0305)
$G4_{sim}$	0.479***	0.718***	0.483***	0.718***	0.402***	0.694***	0.092***	0.308***	0.517***	0.702***
	(0.0364)	(0.0389)	(0.0457)	(0.0268)	(0.0408)	(0.0363)	(0.0181)	(0.0449)	(0.0075)	(0.0069)
$G4_{seq}$	0.588***	0.763***	0.461***	0.596***	0.369***	0.578***	0.161**	0.410***	0.729***	0.911***
	(0.00633)	(0.0742)	(0.0472)	(0.0911)	(0.0480)	(0.0836)	(0.0711)	(0.0621)	(0.0501)	(0.0124)
N	240	240	240	240	240	240	417	414	177	174
R^2	0.820	0.851	0.829	0.847	0.770	0.830	0.534	0.641	0.894	0.949
Hypothesis testing+										
$G1 = G3_{sim}$	0.3147	0.0042	0.3725	0.0010	0.1504	0.0007	0.9886	0.2789		
$G1 = G4_{sim}$	0.0012	0.0079	0.0051	0.0015	0.0002	0.0023	0.0000	0.0000		
$G3_{sim} = G4_{sim}$	0.1079	0.6279	0.1210	1.0000	0.1297	0.6761	0.0011	0.0001		
$G3_{sim} = G3_{seq}$	0.0640	0.0033	0.5612	0.0531	0.7910	0.0001	0.1935	0.7742	0.0394	0.0028
$G4_{sim} = G4_{seq}$	0.0141	0.6100	0.7433	0.2399	0.6180	0.2412	0.3699	0.2237	0.0042	0.0000

Standard errors (adjusted for session-clustering effect) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

+ p-values based on the Wald test are reported

Table D.1: Distribution of RPM scores

RPM score	9 and below	10	11	12	13 and above
No. of Obs.	103	45	63	55	115

D Effect of cognitive ability

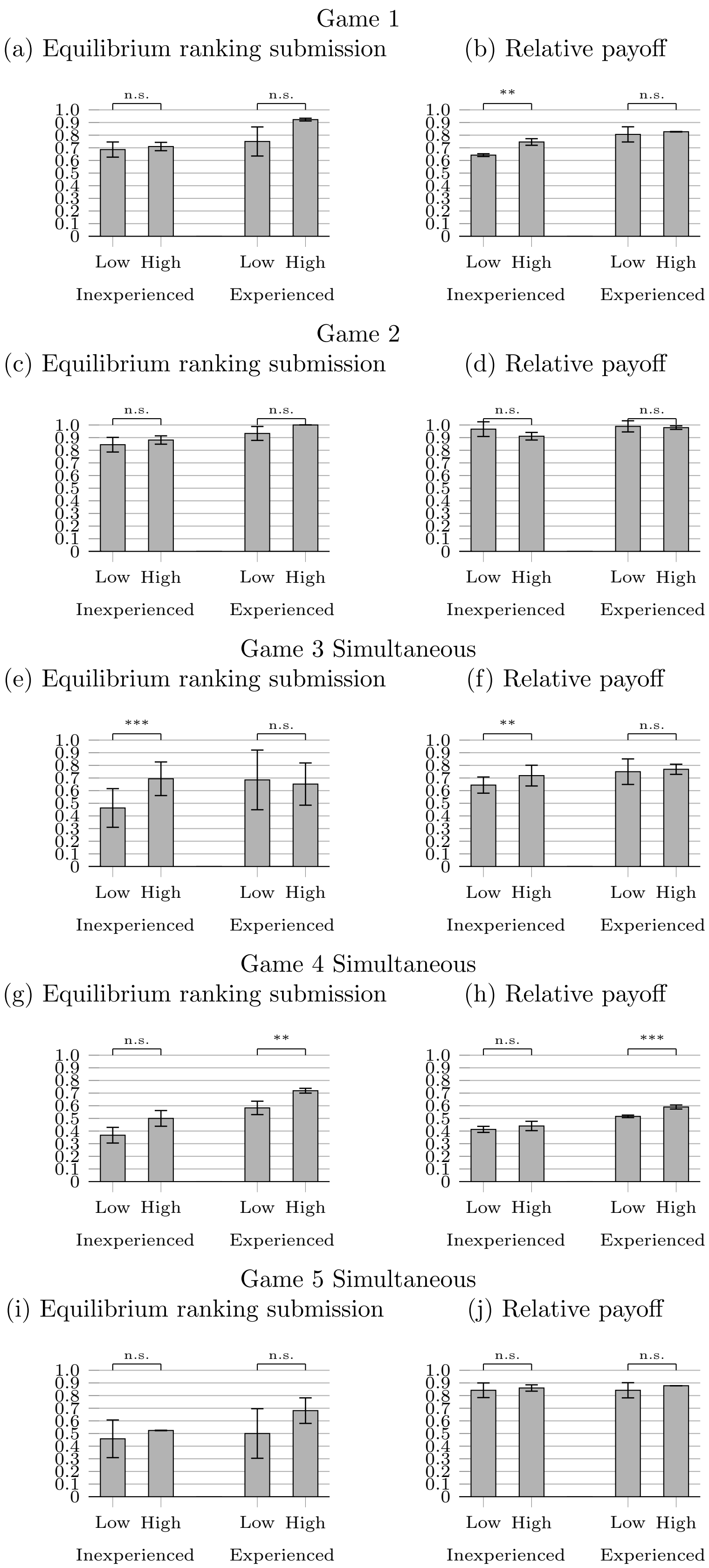
Let us investigate the effect of varying the level of cognitive ability of participants on their behavior and obtained payoffs. Recent studies have reported that the behavior of less strategically sophisticated subjects, captured by subjects' scores on the RPM test, differ (with a negative payoff consequence) from those with more sophisticated subjects in such games as a beauty contest game (Gill and Prowse, 2016) and repeated cooperation games (Proto et al., 2019), as well as well-known mechanisms such as strategy-proof differed acceptance mechanism (DA) and immediate acceptance mechanism (IA)(Basteck and Mantovani, 2018).[19] Basteck and Mantovani (2016) show that learning from experience in the Boston mechanism is related to participants' cognitive abilities. Hanaki et al. (2016) also report that RPM score is correlated with how subjects respond to the behavioral uncertainty of their opponent in a simple two-player coordination game. Considering this, it is possible that the effect of complexities introduced by considering two sectors depends on participants' cognitive abilities.

In this section, we compare the behavior and resulting payoff to participants with high and low cognitive ability. The average RPM score of our 381 participants was 10.85, with a standard deviation of 2.65. The median RPM score was 11. We categorize our participants into three categories based on their RPM scores. "High" and "low" groups are those with RPM score 13 or above and 9 or below, respectively. There were 115 and 103 participants in the "high" and "low" ability categories, respectively. The remaining 163 participants whose RPM scores are either 10, 11, or 12 are in the "middle" group. See Table D.1 for a more detailed distribution of RPM scores.

We measure participants' behavior based on the average frequency of submitting Pareto-dominant equilibrium ranking. For simultaneous treatment, Sectors 1 and 2 are jointly considered in two-sector games. For sequential treatment, we consider the equilibrium ranking submission in Sector 1 and conditionally optimal ranking submission in Sector 2. The payoffs are normalized to the equilibrium payoff (relative payoff). As before, we consider inexperienced and experienced participants and take the average across repetitions for both measures (note that participants' roles are not fixed across repetitions).

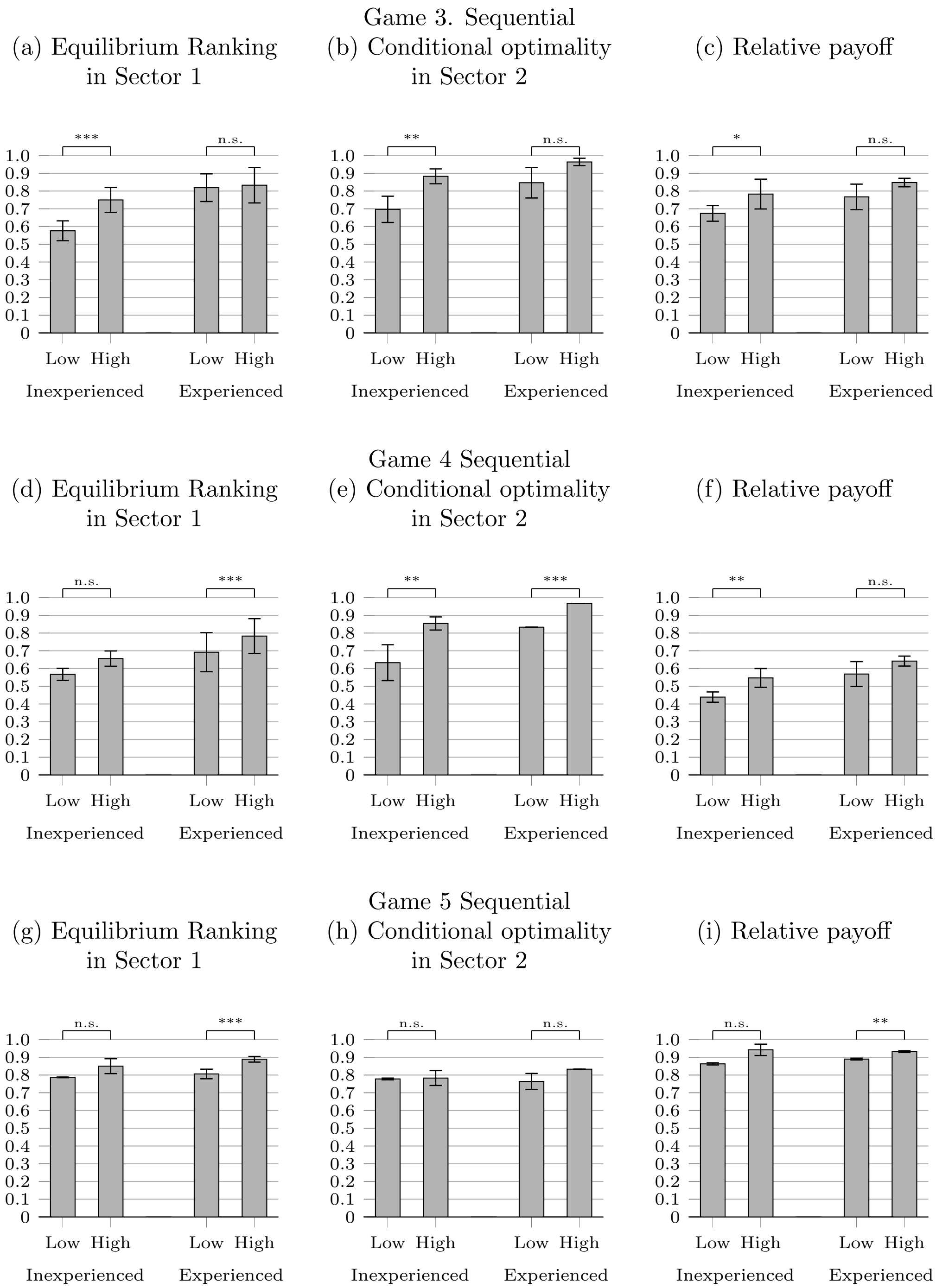
[19] Basteck and Mantovani (2018) also report that DA is better than IA in terms of providing a level playing field to less strategically sophisticated subjects.

Figure D.1: Cognitive ability, equilibrium behavior, and payoff in simultaneous treatment



Note. Based on the estimated coefficient of game dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level based on the Wald test.

Figure D.2: Cognitive ability, equilibrium behavior, and payoff in sequential treatment



Note. Based on the estimated coefficient of game dummies. Error bars show two standard errors range. Standard errors are corrected for session-level clustering effect. ***, **, and * stand for statistical significance at the 1%, 5%, and 10% levels, respectively. n.s., means the difference is not statistically significant at the 10% level based on the Wald test.

Figures D.1 and D.2 show the results for simultaneous and sequential treatments, respectively.[20] We observe that, when inexperienced, the "high" group participants submit the equilibrium ranking or the conditionally optimal ranking more frequently. As a result, these participants obtain higher relative payoffs than "low" group participants. However, the differences are marginally significant (the 10% level) only for Game 3 in the simultaneous treatment and Games 3 and 4 in the sequential treatment, insignificant for the other games.

The advantage for the "high" group observed among inexperienced participants disappears among experienced participants except for Games 4 and 5, in which the two sectors are asymmetric. This suggests that, on the one hand, gaining experience helps to reduce the effect of differences in participants' cognitive ability to achieve equilibrium behavior and obtain a higher payoff. On the other hand, it also suggests that the required amount of experience to overcome the impact of cognitive ability increases with the complexity of the allocation problem caused by the existence of multiple sectors that are asymmetric and interrelated.

Table D.2: Regressions corresponding to Figure D.1: Simultaneous treatment. Equilibrium Ranking submission

	Game 1	Game 2	Game 3	Game 4	Game 5
Low, Inexp	0.686***	0.844***	0.463*	0.367**	0.458*
	(0.060)	(0.058)	(0.153)	(0.062)	(0.149)
High, Inexp	0.710***	0.881***	0.694**	0.500***	0.524***
	(0.033)	(0.033)	(0.133)	(0.062)	(0.002)
Low, Exp	0.750***	0.933***	0.685*	0.583***	0.500*
	(0.115)	(0.055)	(0.236)	(0.053)	(0.196)
High, Exp	0.923***	1.000***	0.652**	0.719***	0.681***
	(0.011)	(0.000)	(0.167)	(0.019)	(0.101)
Mid, Inexp	0.580***	0.840***	0.484***	0.375**	0.500**
	(0.021)	(0.033)	(0.002)	(0.084)	(0.105)
Mid, Exp	0.810***	0.977***	0.750***	0.722**	0.567***
	(0.061)	(0.009)	(0.026)	(0.187)	(0.017)
N	129	114	84	81	87
R^2	0.868	0.963	0.775	0.766	0.811
Hypothesis testing+					
Low = High (Inexp)	0.790	0.609	0.001	0.362	0.686
Low = High (Exp)	0.188	0.280	0.939	0.028	0.154

Standard errors (adjusted for session-clustering effect) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

+ p-values based on the Wald test are reported

[20]The averages reported in the figure are based on the estimated coefficient obtained from running the the following linear regression for each panel and each type of the subjects: $Y = \beta_1 LowInexp + \beta_2 HighInexp + \beta_3 LowExp + \beta_4 HighExp + \mu$ where $LowInexp$ is a dummy variable that takes the value 1 if the inexperienced participant is in the "Low" group and value 0, otherwise. $HighInexp$, $LowExp$, and $HighExp$ are dummy variables that are defined in a similar manner. The standard errors are corrected for the session-clustering effect. The results of these regressions are reported in Tables D.2 to reg:CAmeanRPseq.

Table D.3: Regressions corresponding to Figure D.1: Simultaneous treatment. Relative Efficiency

	Game 1	Game 2	Game 3	Game 4	Game 5
Low, Inexp	0.642***	0.967***	0.644***	0.413***	0.842***
	(0.011)	(0.058)	(0.064)	(0.024)	(0.058)
High, Inexp	0.746***	0.911***	0.719***	0.440***	0.860***
	(0.026)	(0.030)	(0.082)	(0.037)	(0.025)
Low, Exp	0.806***	0.989***	0.750***	0.516***	0.842***
	(0.060)	(0.044)	(0.101)	(0.010)	(0.060)
High, Exp	0.827***	0.979***	0.769***	0.590***	0.878***
	(0.002)	(0.014)	(0.040)	(0.016)	(0.000)
Mid, Inexp	0.667***	0.933***	0.633***	0.467***	0.814***
	(0.045)	(0.035)	(0.022)	(0.023)	(0.030)
Mid, Exp	0.842***	0.994***	0.816***	0.597***	0.860***
	(0.034)	(0.005)	(0.013)	(0.070)	(0.004)
N	129	114	84	81	87
R^2	0.932	0.978	0.960	0.963	0.985
Hypothesis testing+					
H0: Low = High (Inexp)	0.034	0.132	0.024	0.686	0.844
H0: Low = High (Exp)	0.730	0.836	0.902	0.001	0.582

Standard errors (adjusted for session-clustering effect) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

+ p-values based on the Wald test are reported

Table D.4: Regressions corresponding to Figure D.2: Sequential Treatment. Equilibrium Ranking in Sector 1

	Game 3	Game 4	Game 5
Low, Inexp	0.576***	0.567***	0.787***
	(0.058)	(0.034)	(0.002)
High, Inexp	0.750***	0.656***	0.850***
	(0.070)	(0.043)	(0.042)
Low, Exp	0.819***	0.692***	0.806***
	(0.078)	(0.110)	(0.027)
High, Exp	0.833***	0.783***	0.889***
	(0.100)	(0.098)	(0.016)
Mid, Inexp	0.792***	0.550***	0.821***
	(0.029)	(0.014)	(0.007)
Mid, Exp	0.719***	0.844***	0.889***
	(0.017)	(0.087)	(0.027)
N	90	96	90
R^2	0.875	0.835	0.956
Hypothesis testing+			
Low = High (Inexp)	0.001	0.324	0.246
Low = High (Exp)	0.943	0.005	0.006

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Standard errors (adjusted for session-clustering effect) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

+ p-values based on the Wald test are reported

Table D.5: Regressions corresponding to Figure D.2: Sequential Treatment. Conditional Optimality

	Game 3	Game 4	Game 5
Low, Inexp	0.697***	0.633***	0.778***
	(0.074)	(0.101)	(0.005)
High, Inexp	0.883***	0.854***	0.783***
	(0.042)	(0.037)	(0.042)
Low, Exp	0.847***	0.833***	0.764***
	(0.086)	(0.000)	(0.045)
High, Exp	0.964***	0.967***	0.833***
	(0.021)	(0.000)	(0.000)
Mid, Inexp	0.868***	0.700***	0.821***
	(0.069)	(0.042)	(0.047)
Mid, Exp	0.895***	0.978***	0.785***
	(0.010)	(0.012)	(0.013)
N	90	96	90
R^2	0.949	0.934	0.962
Hypothesis testing+			
Low = High (Inexp)	0.010	0.040	0.914
Low = High (Exp)	0.166	0.000	0.219

Standard errors (adjusted for session-clustering effect) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

+ p-values based on the Wald test are reported

Table D.6: Regressions corresponding to Figure D.2: Sequential Treatment. Relative Efficiency

	Game 3	Game 4	Game 5
Low, Inexp	0.674***	0.439***	0.863***
	(0.044)	(0.029)	(0.006)
High, Inexp	0.783***	0.547***	0.942***
	(0.084)	(0.053)	(0.033)
Low, Exp	0.767***	0.569***	0.890***
	(0.072)	(0.070)	(0.005)
High, Exp	0.848***	0.642***	0.932***
	(0.024)	(0.028)	(0.005)
Mid, Inexp	0.769***	0.479***	0.922***
	(0.045)	(0.063)	(0.025)
Mid, Exp	0.748***	0.736***	0.942***
	(0.024)	(0.073)	(0.001)
N	90	96	90
R^2	0.969	0.937	0.991
Hypothesis testing+			
Low = High (Inexp)	0.072	0.020	0.134
Low = High (Exp)	0.461	0.178	0.023

Standard errors (adjusted for session-clustering effect) in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

+ p-values based on the Wald test are reported