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Price stickiness and strategic uncertainty: An experimental study ☆

Yukihiko Funaki [a], Kohei Kawamura [a], Kozo Ueda [a,*], Nobuyuki Uto [b]

[a] Waseda University, Japan
[b] Matsumoto University, Japan

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A B S T R A C T

We identify a minimal set of components to generate price stickiness by a laboratory experiment on an oligopolistic price setting game. Our design involves repeated aggregate shocks to the market but features no uncertainty in their timing and magnitude, no real-nominal distinction, or no need to compute the best response to the prices of the other subjects. We find persistent price stickiness when prices are strategic complements and fully anticipated shocks lower the equilibrium price. By exploring the causes of the observed downward stickiness, we find that it stems from strategic uncertainty regarding beliefs about others' prices, compounded by strategic complementarity and an asymmetric payoff structure.

1. Introduction

Price stickiness is one of the key variables for optimal monetary policy, and macroeconomic models often introduce price stickiness by assuming explicit price frictions in price setting such as menu costs, limited opportunities to revise prices, or informational rigidity. However, micro-level empirical studies such as Bils and Klenow (2004) have indicated that actual price frictions are not as pronounced as are often assumed in standard macroeconomic models. It has also been known that strategic complementarity in price setting enhances the effect of monetary policy, but for most standard models, an explicit price friction is necessary to generate any real effect (e.g. Woodford, 2003a). Alternative sources of price stickiness based on bounded rationality combined with strategic complementarity have been suggested in the experimental economics literature (Fehr and Tyran, 2001, 2008 for money illusion; Petersen and Winn, 2014 and Cooper et al., 2021 for bounded rationality). Disentangling different types of bounded rationality at work has proved difficult as there can be numerous confounding factors even in the laboratory. In the absence of frictions, what is then the "minimal" set of components that induce price stickiness? Can strategic complementarity of prices alone cause stickiness?

We report on a price setting experiment with identical firms and fully anticipated shocks but with no explicit friction, no uncertainty in fundamentals, no real-nominal distinction (hence no room for money illusion), or no need to calculate the best response given the belief about the other subjects' prices. Specifically, our simple design draws from a model of a market where demand is derived from a constant elasticity of substitution (CES) utility function (e.g. Dixit and Stiglitz, 1977; and Blanchard and Kiyotaki, 1987) widely adopted in the macroeconomics literature. We also minimize subjects' cognitive burden by providing them with assistance to find

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* Corresponding author.
E-mail addresses: funaki@waseda.jp (Y. Funaki), kkawamura@waseda.jp (K. Kawamura), kozo.ueda@waseda.jp (K. Ueda), nobuyuki.uto@gmail.com (N. Uto).

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the profit-maximizing price given the other subjects' prices, as well as a plenty of opportunities to learn how the price setting game works. These design features leave us with two primary factors to examine slow price adjustment, namely i) how their beliefs about the other subjects' prices change; and ii) the extent to which the subjects' prices are consistent with profit maximization given their (stated) beliefs.

In the laboratory, we observe price stickiness when prices are strategic complements and cost shocks are negative. When prices are strategic substitutes or cost shocks are positive, no significant price stickiness is observed. We also find that the observed stickiness is primarily due to slow adjustment of subjects' beliefs about the others' prices, as consistent with the existing experimental literature. Furthermore, price stickiness becomes less pronounced as subjects experience more shocks, but does not disappear.

We then explore the causes of the observed downward stickiness and find that it stems from strategic uncertainty about others' prices, compounded by strategic complementarity and an asymmetric payoff structure. Stickiness after negative cost shocks is accompanied by slow adjustment of stated beliefs about the others' prices and mild tendency to set a price slightly above the best response to their beliefs. Furthermore, through a control treatment where the profit functions lead to the same equilibrium price and profit as in the price setting game but different profits out of the equilibrium, we demonstrate that price stickiness is caused not by strategic complementarity alone, but by the combination of strategic complementarity *and* the asymmetry of the profit function in the price setting game. Under these conditions, strategic uncertainty regarding the other firms' prices makes a faster adjustment to the equilibrium following a negative cost shock disproportionately "risky" in the sense that the firm may incur a substantive loss in the adjustment process.

Overall, our main contribution is to show that price stickiness can emerge without explicit frictions in price adjustments, uncertainty in fundamentals, money illusion or cognitive limitations. Instead, it arises from strategic uncertainty, combined with strategic complementarity and an asymmetric payoff structure, which together justify slow adjustments. In this respect, we refine the understanding of the factors contributing to price stickiness, narrowing them down from those identified in previous works, such as Fehr and Tyran (2001, 2008) and Petersen and Winn (2014), which include money illusion and cognitive limitations. Following the classification proposed by Bao et al. (2013), our experiments focus on a *learning-to-forecast* framework. By providing subjects with simple and clear guidance, we deliberately exclude complexities associated with *learning-to-optimize* processes.

Strategic uncertainty about other participants' actions, beliefs, or higher-order beliefs plays a critical role in how markets reach equilibrium. Cason and Friedman (1997) and Fehr and Tyran (2001) show that when all players are human, adjustments to a new equilibrium are slower compared to settings where players compete against robots. These results suggest that strategic uncertainty about others delays convergence to equilibrium. In a similar vein, experimental studies such as Heinemann et al. (2009), Cheung et al. (2014), Akiyama et al. (2017), Arifovic and Jiang (2019), Fehr et al. (2019), and Castillo and Dianat (2021) generally find that strategic uncertainty leads to sustained deviations from equilibrium. This study contributes to this literature by explicitly examining the dynamics of slow convergence to equilibrium and identifying a specific mechanism through which strategic uncertainty, in combination with strategic complementarity and an asymmetric payoff structure, leads to such slow convergence.

Our findings highlight that an asymmetric payoff structure, where setting a lower price than the best response leads to disproportionately lower profits than when setting a higher price, is crucial in generating price stickiness. Asymmetric payoff structures are not unrealistic in the macroeconomic context: rather, they naturally arise from conventional demand curves derived from the CES utility function, as demonstrated in our model. The asymmetric response of prices to shocks observed in our experiments is consistent with what has been widely discussed in the macroeconomics literature (e.g., Tobin, 1972; DeLong and Summers, 1988; Ball and Mankiw, 1994). Furthermore, the role of the asymmetric payoff structure we identify aligns also with the experimental findings by Cooper et al. (2021).

Our design builds on those of Fehr and Tyran (2001, 2008) who observe stickiness in price-setting games and attribute it to money illusion. In particular, Fehr and Tyran (2008) identify the importance of the strategic environment in price stickiness. In a closely related setup with and without the real/nominal distinction, Petersen and Winn (2014) find that price stickiness is more strongly associated with difficulty in finding the payoff-maximizing price than money illusion. Cooper et al. (2021) introduce repeated identical shocks into a similar price setting game and find that convergence to equilibrium play under strategic complementarity is not immediate even after the subjects experience multiple shocks, and that convergence is much slower after downward shocks than upward shocks.[1] Like a treatment in Petersen and Winn (2014), all variables in our experiments are in real terms, so that we rule out money illusion, and highlight the profit-maximizing price given the other subjects' average price in profit tables, in order to eliminate concerns regarding cognitive limitations. Unlike these earlier studies, we elicit not only beliefs about the other subjects' prices but also confidence on the beliefs, so as to study each subject's response to the stated belief and the subjective degree of uncertainty about other subjects' strategies. In addition, we study the cause of the observed downward stickiness by running additional treatments where the profit tables have the payoffs that are symmetric relative to the payoff from the best response. The findings from the treatments with symmetric payoffs are consistent with our argument that the observed downward stickiness is caused by the specific type of payoff asymmetry described earlier.

This paper is also related to recent experimental research on transition among efficient and inefficient equilibria in dynamic coordination games. Smerdon et al. (2020), Andreoni et al. (2021), and Duffy and Lafky (2021) introduce gradual changes in the experimental subjects' preferences that make the initial focal equilibrium inefficient, and study the speed at which transitions to an

[1] Bao et al. (2012) also introduce multiple shocks into a price setting game à la Fehr and Tyran (2008), but at the same time they add more exogenous uncertainty to the environment (for example, shocks are heterogeneous, their timing is not announced beforehand, and payoff tables are not revealed). In contrast, the main aim of our design is to minimize exogenous uncertainty.

efficient equilibrium under various circumstances.[2] Smerdon et al. (2020) and Andreoni et al. (2021) find that an inefficient outcome ("bad norm") persists especially when there is greater uncertainty in the stochastic process of changes in individual preferences. Duffy and Lafky (2021) find the transition can be slow even when the process of preference changes is deterministic and known to the subjects. Our design is very different from and much simpler than in those studies, since all players share homogeneous payoff structure and there is a unique equilibrium in any period. Our primary focus is on the speed at which transition from one unique equilibrium to another unique equilibrium occurs when the payoff structure changes deterministically, through which we explore minimal components that cause slow adjustments.

Broadly speaking, our study belongs to the strand of experimental macroeconomics. See Amano et al. (2014), Cornand and Heinemann (2014a), and Duffy (2016) for comprehensive surveys. While agents' reaction to shocks have been studied extensively in this literature, the experimental designs tend to be much more complex than ours and thus the sources of non-equilibrium behaviors and expectations are more difficult to extrapolate. One strand of the literature studies price dynamics by introducing price rigidity explicitly into the experimental design.[3] Expectations-based New Keynesian models have also been tested experimentally.[4] These studies typically focus on the effect of policy intervention on forecasts/expectations in the presence of exogenous uncertainty. Lambsdorff et al. (2013), Cornand and Heinemann (2014b) and Baeriswyl et al. (2021) study reaction to public information in setups that feature beauty contests.

The macroeconomics literature on price rigidity has emphasized the importance of strategic complementarity (Woodford, 2003a; Wang and Werning, 2022; Ueda, 2023). Woodford (2003b) argued that on top of strategic complementarity, higher-order expectations in an imperfect information framework play an important role in persistent price dynamics (see also Nimark, 2008 and Angeletos and Lian, 2016). While we stress the role of expectations in explaining price rigidity, unlike the framework proposed by Woodford (2003b), our design does not involve any informational imperfection with respect to the state of the economy. Other behavioral determinants of price rigidity, such as cognitive discounting and level-k reasoning, have been explored (Gabaix, 2020; Garcıa-Schmidt and Woodford, 2019; Farhi and Werning, 2019) especially in relation to under-reaction. However, our design is based on a static model and makes discounting inconsequential to decision making. The observed patterns of price adjustment cannot be systematically described by a cognitive hierarchy model, as many subjects appear to make reasonable price adjustments even after the very first shock, which makes it difficult to incorporate level-0 reasoning into our explanation.

Using survey data, Alvarez and Hernando (2005) suggest that firms are more responsive in price reduction than price increase with respect to changes in demand and competitors' prices, while they are more responsive in price increase with respect to cost shocks. This is consistent with our result that the adjustment to the equilibrium price is faster for the positive cost shock than for the negative cost shock. We argue that the asymmetric response is due to the payoff/profit structure under uncertainty regarding competitors' prices.[5]

The rest of this paper is structured as follows. Section 2 presents our experimental design, and we discuss the results from our experiment in Section 3. Section 4 concludes.

2. Experimental design

2.1. Model

Let us first describe the theoretical model our experimental design is based on. Each subject is a firm that faces competition among n firms and sets his/her price P_{it} in every period t (Dixit and Stiglitz, 1977; Blanchard and Kiyotaki, 1987; and Woodford, 2003a). The demand for firm i's product at t is denoted by $Y_{it} = (P_{it}/\bar{P}_{it})^{-\varepsilon} Y_t$, where ε and Y_t represent the price elasticity ($\varepsilon > 1$) and aggregate demand at t, respectively. Following Fehr and Tyran (2001, 2008), we assume that the average price $\bar{P}_{it}$ is defined by the average price of the other $n-1$ firms. That is, each firm's own price is excluded from the calculation of $\bar{P}_{it}$. In order to incorporate strategic complementarity/substitutability into a simple setup, we assume that the cost of production is given by $c\bar{P}_{it}^{\zeta} Y_{it}$, where c and ζ represent a cost parameter and the degree of strategic complementarity ($\zeta > 0$)/substitutability ($\zeta < 0$), respectively. Under those assumptions, subject i's profit is given by

$$\Pi_{it} = \frac{P_{it} - c\bar{P}_{it}^{\zeta}}{\bar{P}_{it}} Y_{it}, \tag{1}$$

which leads to the profit-maximizing price

$$P_{it} = \frac{\varepsilon}{\varepsilon - 1} c\bar{P}_{it}^{\zeta}. \tag{2}$$

[2] Fehr and Tyran (2007) experimentally study equilibrium selection in a price setting game, with treatments where payoffs are presented in real and nominal terms, respectively.

[3] See for example, Wilson (1998), Davis and Korenok (2011), Noussair et al. (2015), and Magnani et al. (2016).

[4] Adam (2007), Assenza et al. (2013), Orland and Roos (2013), Luhan and Scharler (2014), Noussair et al. (2015), Kryvtsov and Petersen (2015), Pfajfar and Zakelj (2016), and Giamattei (2022).

[5] Angeletos et al. (2020) argue that professional forecasters' expectations of inflation under-react initially but over-shoot later on.

Table 1
Experimental Design.

Panel A. Universal parameters	
Representation of profits	Π_{it}
Group size	$n = 5$
End of period information feeback	$\bar{P}_t, \Pi_{it}$
Choice variable	$P_{it} \in \{1, 2, \dots, 20\}$
Number of periods	60 (30 in some)
The timing of shocks	$t = 16, 31, 36, 41, 46, 51, 56$
Price elasticity	$\varepsilon = 6$
Aggregate demand (equilibrium profits)	$Y_t = 5$
Panel B. Treatment-specific parameters	
Theoretical price under cost decrease (Down)	$\bar{P}_t^* = 7$
Theoretical price under cost increase (Up)	$\bar{P}_t^* = 15$
Strategic complementarity (SC)	$\zeta = 0.5$
Strategic substitutability (SS)	$\zeta = -0.5$
Menu costs (MC)	$\kappa = 0$ or 0.1
Panel C. Treatments	The number of participants
SC	
Down at $t = 16$	35 (10)
Up at $t = 16$	25 (5)
Down at $t = 16$ with MC	30
Up at $t = 16$ with MC	15
SS	
Down at $t = 16$	20 (10)
Up at $t = 16$	10 (5)
Down at $t = 16$ with MC	30
Up at $t = 16$ with MC	15
Symmetric profits and SC	
Down at $t = 16$	30
Up at $t = 16$	30

Notes: Figures in parentheses indicate the number of participants in the treatments where the number of periods is 30. Parameter c is calibrated at 2.19.

It is easy to see that the optimal price is increasing (decreasing) in the other firms' average price $\bar{P}_{it}$, when ζ is positive (negative). Therefore a positive (negative) ζ implies strategic complementarity (substitutability).[6]

2.2. Procedures and parameter values

The experiments were conducted at Waseda University in Tokyo from November 2017 to July 2018. We ran 9 sessions with 30 subjects in each session, and all 270 participants were students in various majors such as economics, education, humanities, law, commerce, politics, engineering, etc. from Waseda University. The experiments were computerized with z-Tree (Fischbacher, 2007). Each session lasted around 90 minutes, and the show-up payment was JPY1000 (around \$8.8), and average earnings were JPY984 (around \$8.7).[7] No subject participated in more than one session. Each market/group consisted of five subjects ($n = 5$). Table 1 summarizes the parameter values of interest for each treatment. The group membership was randomly determined and fixed throughout each session to allow potential learning and coordination. The degree of strategic complementarity/substitutability ζ was set at either 0.5 or -0.5.[8]

The shocks to the market were in terms of the production cost that was common across all firms in the market. All shocks were exogenous, fully anticipated and occurred at the beginning of a period before the firms set the price for the period. The cost was either high or low, and a shock was a transition between the high cost and the low cost. A positive cost shock leads to a higher theoretical price corresponding to the high cost, and a negative cost shock leads to a lower theoretical price corresponding to the low cost. In theory, the model has a unique equilibrium for each value of the cost parameter, and we denote the theoretical price without uncertainty by P_t^*. The parameter values were set so that $P_t^* = 15$ for the high cost and $P_t^* = 7$ for the low cost. These correspond to changes in the cost parameter c, such that when $\zeta = 0.5$, $c = 3.22$ and 2.19, respectively; and when $\zeta = -0.5$, $c = 48.4$ and 15.4, respectively.

6 In other words, $\partial^2\Pi_{it}/\partial P_{it}\partial\bar{P}_{it}$ is positive (negative) when ζ is positive (negative). It should also be noted that, based on the CES utility function, the optimal price is determined as an interior solution, unlike in Bertrand and Hotelling models.

7 We convert Japanese yen into US dollars at the exchange rate of \$1 = JPY113, which was the average rate at the time when the experiments were conducted.

8 In Fehr and Tyran (2001, 2008), the (implied) strategic parameter corresponding to ζ was either 1 or -1, except for the neighborhood of the equilibrium price where the slope of the best response was made flat. According to footnote 7 in Kimball (1995), ζ is estimated to be positive and lower than one. According to equation (1.34) and Table 3.1 in Woodford (2003a), ζ lies between -1.25 and 0.94.

Table 2
Profit Tables when Prices are Strategic Complements.

The average price of the other firms in your group

Your price	4	5	6	7	8	9	10	11	12	13	14	15
4	-0.465	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
5	0.206	5.000	-8.186	-10	-10	-10	-10	-10	-10	-10	-10	-10
6	0.179	10	5.000	2.247	-2.819	-10	-10	-10	-10	-10	-10	-10
7	0.114	10	5.053	5.000	5.011	4.092	1.209	-5.009	-10	-10	-10	-10
8	0.071	8.254	3.646	4.088	5.000	5.987	6.720	6.761	5.506	2.139	-4.405	-10
9	0.045	5.380	2.478	2.926	3.823	5.000	6.361	7.779	9.060	9.927	9.996	8.764
10	0.029	3.554	1.678	2.038	2.753	3.745	5.000	6.496	8.187	9.990	10	10
11	0.019	2.399	1.151	1.424	1.961	2.728	3.736	5.000	6.524	8.300	10	10
12	0.013	1.656	0.804	1.006	1.405	1.983	2.759	3.757	5.000	6.504	8.277	10
13	0.009	1.168	0.572	0.723	1.019	1.452	2.042	2.814	3.792	5.000	6.460	8.188
14	0.007	0.841	0.415	0.528	0.749	1.075	1.524	2.117	2.878	3.831	5.000	6.406
15	0.005	0.617	0.306	0.391	0.558	0.806	1.150	1.607	2.199	2.947	3.873	5.000

Your price	7	8	9	10	11	12	13	14	15	16	17	18
7	-1.087	-2.939	-6.683	-10	-10	-10	-10	-10	-10	-10	-10	-10
8	-0.167	-0.694	-1.873	-4.169	-10	-10	-10	-10	-10	-10	-10	-10
9	0.076	-0.034	-0.368	-1.116	-10	-10	-10	-10	-10	-10	-10	-10
10	0.124	0.146	0.099	-0.093	-10	-10	-10	-10	-10	-10	-10	-10
11	0.118	0.175	0.223	0.230	5.000	-1.581	-6.029	-10	-10	-10	-10	-10
12	0.098	0.159	0.231	0.304	10	5.000	2.253	-0.336	-3.588	-7.971	-10	-10
13	0.078	0.132	0.204	0.292	10	6.766	5.000	3.796	2.453	0.646	-1.887	-5.411
14	0.061	0.106	0.170	0.253	10	6.692	5.517	5.000	4.568	3.990	3.100	1.742
15	0.048	0.085	0.138	0.211	10	5.981	5.175	5.002	5.000	5.001	4.898	4.596
16	0.037	0.067	0.112	0.173	8.854	5.117	4.551	4.548	4.739	5.000	5.259	5.459
17	0.030	0.054	0.090	0.141	7.311	4.291	3.885	3.962	4.228	4.591	5.000	5.420
18	0.023	0.043	0.072	0.115	6.010	3.567	3.269	3.380	3.664	4.049	4.502	5.000

Notes: We magnify a relevant part of the profit tables. They correspond to the case where $\zeta = 0.5$ (strategic complementarity), and the equilibrium prices are 7 and 15 in the top and bottom tables, respectively. The full tables are provided in the Online Appendix.

In some treatments, a shock occurred only at $t = 16$ and the final period was $t = 30$. In the other treatments, the subjects encountered a shock at $t = 16, 31, 36, 41, 45, 51, 56$, and the final period was $t = 60$. In the treatments with multiple shocks, the subjects initially faced shocks less frequently (at $t = 16$ and 31) so that they could acclimatize to the environment, and then experienced a shock every five periods thereafter. All subjects were informed of the schedule of all shocks before the first period started, and reminded of each shock at the beginning of every period with a shock.

In each period t, each subject i chose their price $P_{it} \in \{1, 2, \ldots, 20\}$, and stated their belief/guess about the average price of the other subjects, corresponding to $\bar{P}_{it}$, and the degree of confidence about their belief by choosing an integer from one to six, where larger values indicate higher confidence.[9] At the end of every period, each subject i received feedback on the realized profit Π_{it} and the realized average price of the others $\bar{P}_{it}$.

In order to reduce the subjects' cognitive burden, we did not present the model to the subjects, including the cost parameter c. Instead, they were given two profit tables as shown in Table 2 we generated from the model we described in Section 2.1 for each value of the cost parameter.[10] The tables showed the profits in a matrix form given the combination of $(P_{it}, \bar{P}_{it})$. Moreover, the tables were printed on separate sheets in different color, namely one in red and the other in blue, and we told the subjects which colored sheet to look at every time a cost shock occurred. Also on the profit tables, we highlighted in gray every cell that maximizes profits given each belief about $\bar{P}_{it}$.

[9] We chose not to use monetary incentives for the elicitation of beliefs and confidence, since i) simple incentive schemes to elicit such beliefs are typically not incentive compatible for truth-telling; and ii) an incentive compatible elicitation mechanism would be complex in the setup, which may contradict our aim of minimizing the cognitive burden on the subjects. Our belief elicitation was administered through a simple question ("(w)hat do you think is the average price of the other firms?") and the term "the average price of the other firms" also appears in the payoff table, to draw a direct link between the belief and the price. As we will see shortly in the next section, the subjects largely best respond to their stated beliefs, and thus we posit that they effectively reflect the beliefs the subjects' individual decisions are based on. See Schotter and Trevino (2014), Schlag et al. (2015), and Charness et al. (2021) for insightful discussions on belief elicitation methods. In particular, Charness et al. (2021) note that non-incentivized responses "seem to do as well as rather complex incentivized methods".

[10] Fehr and Tyran (2001, 2008) and Petersen and Winn (2014) also gave their subjects payoff tables but not the model that generates them.

The subjects were required to solve exercises after the computer read out the instructions already given to them. The exercises were especially designed to check the subjects' understanding of how the average price of the other subjects is calculated, and how to read the profit tables according to their expectation about the average price of the others. The experiment started only after all subjects participated in a session solved all exercises correctly.

Let us note that as described above, all subjects in a group shared the same profit table for each period, which would have made it much easier to think of the average price of the other subjects, unlike the experiments by Fehr and Tyran (2001, 2008) and Petersen and Winn (2014) who gave different profit tables to subjects within the same group.

We made two major modifications with respect to the model and the profit tables. First, in order to avoid collusion, we modified (1) to

$$\Pi_{it} = \begin{cases} \frac{P_{it}-c\bar{P}_{it}^{\zeta}}{\bar{P}_{it}} Y_{it} & \text{if } 1 - c\bar{P}_{it}^{\zeta-1} \leq 0 \\ \frac{P_{it}-c\bar{P}_{it}^{\zeta}}{\bar{P}_{it}\left(1-c\bar{P}_{it}^{\zeta-1}\right)} Y_{it} & \text{if } 1 - c\bar{P}_{it}^{\zeta-1} > 0, \end{cases} \tag{3}$$

which implies that the subjects could not earn collectively higher profits by keeping their prices higher than the theoretical price.[11] The best response given by (2) remains exactly the same after this modification and thus the interpretation of ζ as a strategic parameter is still valid. Second, the profits on the profit tables are truncated so that the maximum profit was 10 and the minimum was -10. This is to avoid income effects and also not to make some cells unnecessarily salient due to extremely large or small numbers.

The subjects received a show-up fee of 1,000 yen ($\approx$ 9.5 USD when the experiment was conducted) and additional earnings based on the average profits they earned in randomly chosen five periods. The conversion rate was 200 yen per point. The average total earning was approximately 2,000 yen. The sessions typically lasted for approximately 100 minutes.[12]

2.3. Hypotheses

We present a set of hypotheses that, when contrasted with the data, collectively allow us to narrow down the set of the underlying causes of price stickiness. All hypotheses are primarily drawn from Fehr and Tyran (2001, 2008), who observed stickiness only under strategic complementarity after negative nominal shocks. Fehr and Tyran (2001) found that under strategic complementarity, downward adjustment was slow after negative nominal shocks but upward adjustment was fast after positive shocks. They attribute this asymmetry to reliance on a "nominal-as-real" heuristic, which discourages downward but not upward adjustment. Petersen and Winn (2014) likewise observed pronounced stickiness following negative shocks, but explain it in terms of the greater cognitive load involved in finding the profit-maximizing price after such shocks.

Since our experimental design features no real-nominal distinction or no need to compute the best response to the prices of the other subjects, it is natural to hypothesize that price stickiness will *not* arise under either negative or positive cost shocks.

Hypothesis 1. Price stickiness is not pronounced under strategic complementarity after negative cost shocks.

Hypothesis 2. Price stickiness is not pronounced under strategic complementarity after positive cost shocks.

These two hypotheses imply a symmetric response to negative and positive cost shocks, in contrast to the asymmetric responses observed by Fehr and Tyran (2001) and Petersen and Winn (2014).

Hypothesis 3. Price stickiness is not pronounced under strategic substitutability.

This hypothesis is drawn from Fehr and Tyran (2008). They argue that stickiness arises when money illusion interacts with strategic complementarity, but not under substitutability, where adjustment is fast. Since our design rules out money illusion, there is no reason to expect stickiness when prices are strategic substitutes.

The set of hypotheses provides a framework for our analysis of price stickiness. If any of these hypotheses are rejected, and stickiness is observed even in the absence of a real–nominal distinction or significant cognitive load, then money illusion or bounded rationality cannot fully account for the observed stickiness. Which hypotheses are rejected, in turn, helps to identify alternative sources of price stickiness.

[11] This is in response to the subjects' choices in pilot sessions where we observed a tendency to keep the price higher to earn higher collusive profits, which prevented convergence to the one-shot theoretical price.

[12] One treatment with strategic complementarity involved an explicit price friction in the form of a menu cost. In the treatment, the subjects had to pay a small cost, $\kappa = 0.1$, every time when they changed their price from that in the previous period. It was clearly explained in the instructions for the treatment and any deduction of menu cost from the market profit when a subject changed the price was also indicated in the feedback at the end of each period. As in the other treatments the equilibrium profit was set at 5, so that the size of the menu cost was not significant. We show the experiment results in Online Appendix.

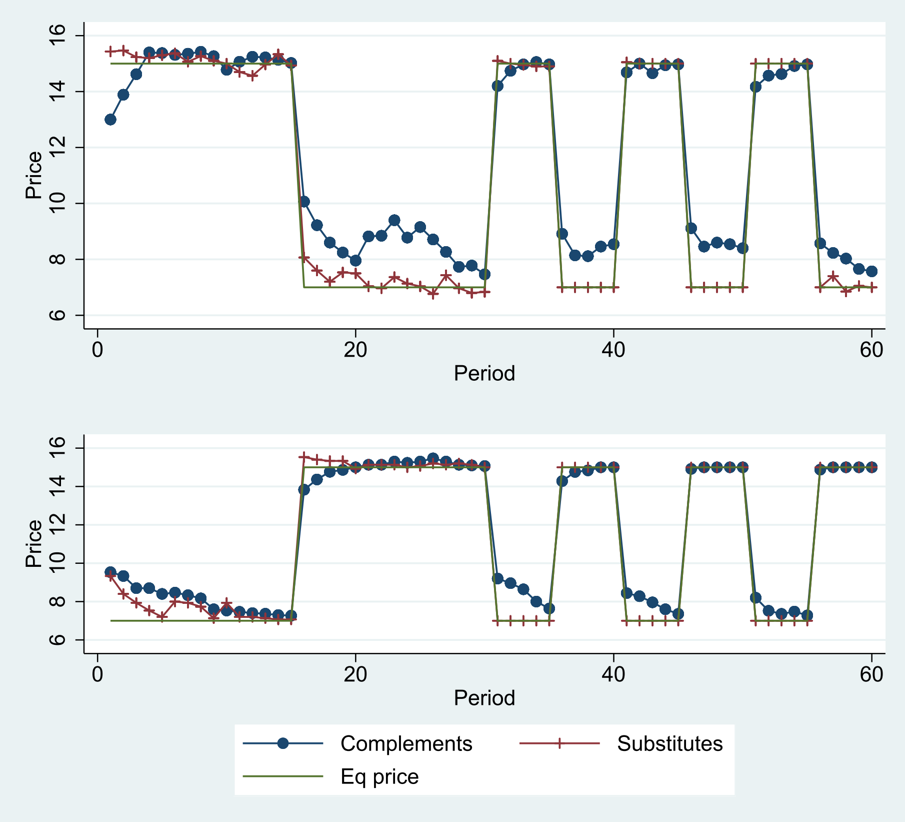


Fig. 1. Evolution of Average Prices. Notes: *Complements* and *Substitutes* represent the treatments under strategic complementarity ($\zeta = 0.5$) and under strategic substitutability ($\zeta = -0.5$), respectively.

3. Experimental results

3.1. Aggregate price movement

Let us first examine the movement of the market price. Fig. 1 and Table 3 show how the price changes in response to shocks for each treatment. Fig. 1 presents the evolution of the average price of all subjects, along with the theoretical price. In all treatments we observe price stickiness after negative cost shocks, particularly in the treatment with strategic complementarity.

We find immediately in Fig. 1 that price adjustment tends to take longer specifically under strategic complementarity after negative cost shocks. Table 3 records the magnitude of deviation from the theoretical price over periods. The average deviation for a treatment is the mean of $\bar{P}_t^j - \bar{P}_t^*$ across j's, where $\bar{P}_t^j$ and $\bar{P}_t^*$ represent the observed mean price of group j in period t and the theoretical price in period t, respectively. We can see that, in the treatments with strategic complementarity, the average deviations are positive and significantly different from zero for a long duration after the first negative cost shock. This readily rejects Hypothesis 1 we discussed in Section 2.3, which indicates that price stickiness is observed even in the absence of money illusion when prices are strategic complements. Meanwhile, Table 3 shows that even under strategic complementarity, the first positive cost shock leads to a statistically significant deviation from the equilibrium only for two periods. This finding supports Hypothesis 2. The asymmetric response to positive and negative cost shocks is observed also by Fehr and Tyran (2001), but they attribute it to money illusion, which is absent here.

Both Table 3 and Fig. 1 indicate that when the prices are strategic substitutes, the average price adjusts to the new theoretical level almost instantaneously after each shock. This result supports Hypothesis 3 and is consistent with Fehr and Tyran (2008).

As an additional remark on the aggregate price movement, we note from Fig. 1 that price stickiness becomes less pronounced as they experience more shocks, while it does not disappear for negative cost shocks under strategic complementarity. The average price often converges to $P = 8$, which is a one unit higher than the theoretical price of 7.

The rejection of Hypothesis 1 together with support for Hypotheses 2 and 3 implies that downward stickiness is observed under strategic complementarity, consistent with the findings of Fehr and Tyran (2001, 2008) and Petersen and Winn (2014). However, the outcome calls for an alternative explanation. In what follows, we examine how price stickiness emerged in our experiment despite the absence of money illusion or the need to compute the profit-maximizing price. Section 3.2 analyzes how our subjects adjusted their beliefs and prices after shocks, and Section 3.3 considers the roles of strategic uncertainty and the payoff structure.

Table 3
Average Deviations from Post-shock Equilibrium Prices.

	Complements		Substitutes	
Periods	Negative cost	Postive cost	Negative cost	Positive cost
16	3.07***	−1.17***	1.07**	0.53
17	2.22***	−0.63**	0.60*	0.40
18	1.60***	−0.23	0.20	0.33
19	1.24***	−0.13	0.53	0.33
20	0.96*	0.00	0.50	−0.07
21	1.82***	0.13	0.03	0.13
22	1.84***	0.13	−0.03	0.13
23	2.40***	0.30*	0.37	0.13
24	1.78**	0.23	0.13	0.00
25	2.16***	0.30	0.03	0.07
26	1.71***	0.47	−0.23	0.20
27	1.27**	0.30	0.43	0.13
28	0.73***	0.13	−0.03	0.20
29	0.78*	0.10	−0.20	0.13
30	0.47*	0.07	−0.17	0.00

Notes: The average deviation of prices is the mean of $\bar{P}_{jt} - \bar{P}^*_t$ across j's, where $\bar{P}_{jt}$ and $\bar{P}^*_t$ represent the mean price of group j in period t and the theoretical price in period t, respectively. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

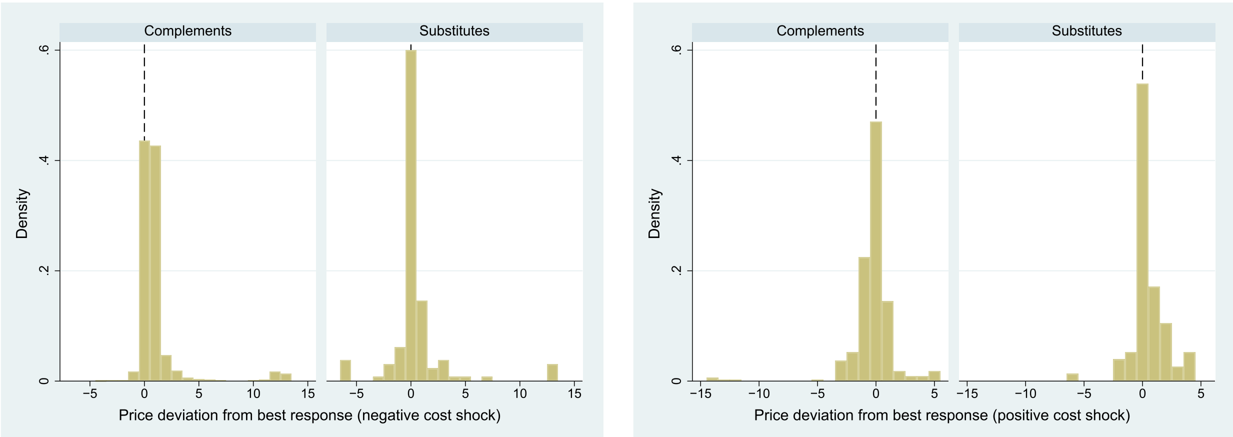


Fig. 2. Histograms of Deviations from Best-Response Prices Based on Beliefs. Notes: The best-response price is defined as the price that maximizes subject i's profit when the average price set by the other subjects in her group equals i's stated belief. The density is calculated from the sample, where periods ≥ 16 and either subject i's own price or i's group average price does *not* equal the respective theoretical price. *Complements* and *Substitutes* represent the treatments under strategic complementarity ($\zeta = 0.5$) and strategic substitutability ($\zeta = -0.5$), respectively.

3.2. Individual decisions

In order to understand why we observe price stickiness under the combination of i) strategic complementarity and ii) negative cost shocks, let us examine our subjects' individual behavior. In what follows, we first examine whether our subjects best respond to their stated beliefs, and then discuss how their beliefs about the other subjects' actions are adjusted with respect to (fully anticipated) shocks. We also look at whether their slow price adjustment increases the individual profits, with respect to the hypothetical scenario where they choose the new theoretical price immediately after each shock, given the *observed* behavior of the other subjects.

3.2.1. Response to stated beliefs

In Fig. 2, we see that the subjects largely best respond to their own stated beliefs in price setting, even out of equilibrium. Fig. 2 presents the histograms of deviations from the best response at the individual level. Best response is defined as the price that maximizes subject i's profit when the average price set by the other subjects in her group equals i's stated belief. The densities are calculated from the sample in the treatments, such that subject i's own price or i's group average price differs from the theoretical price without uncertainty (i.e. any observations that match the equilibrium prediction are excluded) for $t \geq 16$, i.e. after the first shock. Fig. 2 shows that, irrespective of the strategic environment, deviations from the best response to their stated belief are heavily concentrated around a mode of zero. The distributions of the deviations from the stated beliefs strongly suggest that the beliefs do guide, if not completely dictate, subjects' decisions. The observed correspondence between the stated beliefs and the choice of price is also largely consistent with the findings by Fehr and Tyran (2001, 2008).

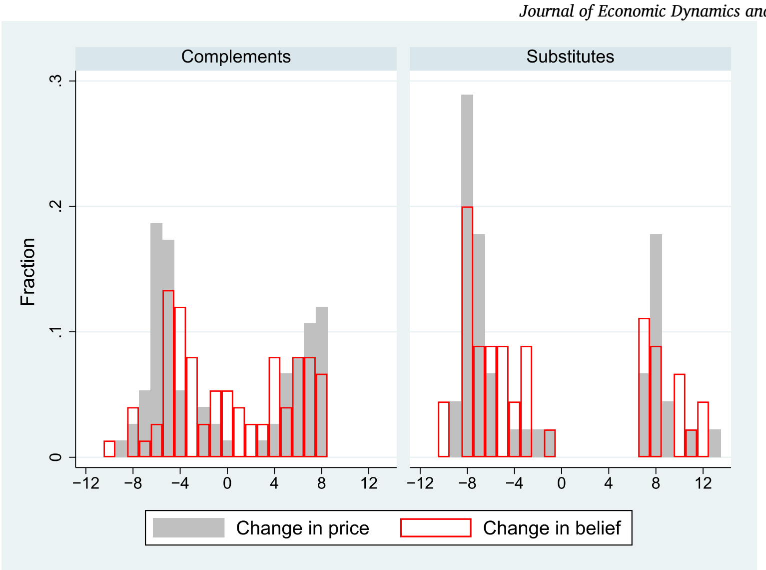


Fig. 3. Histograms of Changes in Prices and Beliefs. Notes: The fraction is calculated from the sample in which the first cost shock occurs (period= 16). *Complements* and *Substitutes* represent the treatments of strategic complementarity ($\zeta = 0.5$) and strategic substitute ($\zeta = -0.5$), respectively.

Meanwhile, the left panel of Fig. 2 also indicates that the deviation from the best response is systematically biased after negative cost shocks under strategic complementarity. For such shocks, the mode is zero (i.e. subjects best responded to the stated belief) but the second-highest density is at one, which implies that a number of subjects' prices were one unit above their best response.

3.2.2. *Changes in beliefs and prices*

Fig. 3 presents how much the subjects change their prices and beliefs immediately after the shocks in period $t = 16$. If the subjects change their prices and beliefs instantaneously according to the new equilibrium, their changes must be either −8 or 8. That is, the belief and price should change from 15 to 7 or the other way round. This is indeed the case in the treatments under strategic substitutability, where not only the prices but also the beliefs are adjusted fast to those in a new equilibrium. On the other hand, when prices are strategic complements, the magnitude of adjustments is much more dispersed. Price and belief adjustments are on average slower, as we see masses of observations between −8 and 8. Moreover, the adjustment of beliefs is more dispersed than the adjustment of prices. This suggests that subjects expect slow changes in other subjects' prices, while the expectations vary across the subjects.

We also note from Fig. 3 that, when prices are strategic complements, immediate individual price adjustments are smaller after negative cost shocks than positive cost shocks. For example, the mode of price adjustment immediately after negative cost shocks is −6, two units higher than the equilibrium, while the mode after cost shocks is 8, which is consistent with the equilibrium. Moreover, the mean and variance of price adjustment for negative cost shocks are −5.72 and 2.30, respectively, and those for positive cost shocks are 7.20 and 1.65, respectively. The difference in the means of price adjustment in absolute terms is statistically significant at the 1% level, indicating that the price adjustment is indeed smaller after negative cost shocks.

We observe a similar pattern for adjustments in beliefs. The mean and variance of belief adjustment after negative cost shocks is are −4.63 and 2.74, respectively, and those after positive cost shocks are 6.64 and 2.39, respectively. The difference in the means of belief adjustment in absolutely terms is again statistically significant at the 1% level, so that the belief adjustment is smaller after negative cost shocks than positive cost shocks.

To summarize, under strategic complementarity, individual beliefs and prices after shocks are not adjusted immediately towards the equilibrium. In particular, as we saw in Fig. 2, there is a systematic upward bias relative to the stated beliefs after negative cost shocks. The levels of belief and price adjustments are dispersed after both positive and negative cost shocks, and the adjustments are smaller after negative cost shocks. Note that immediately after positive cost shocks, the price converges to the equilibrium promptly, as we saw in Section 3.1. This strongly suggests that the marked stickiness after negative cost shocks under strategic complementarity should be attributed to both the upward bias in pricing relative to the stated beliefs, and the smaller adjustments in beliefs.

3.2.3. *Convergence without oscillations*

Before examining the sources of price stickiness in the next subsection, we highlight another important result in the price dynamics. Fig. 1 shows that prices converge smoothly to (the neighborhood of) the equilibrium, without exhibiting oscillations. In a learning-to-forecast experiment, Assenza et al. (2014) document that prices tend to oscillate around the equilibrium under strategic complementarity, attributing this behavior to adaptive expectations.

A key difference here lies in the information provided to the subjects. In our experiment, each shock is represented as a switch to another payoff table from which the subjects can easily derive the new theoretical price without uncertainty. In contrast, the subjects

Table 4
Regression of Deviation from Best Response after Negative Cost Shocks under Strategic Complementarity.

	Pooled	Random effects	Fixed effects	$t = 16$ only	$t = 16, 31, \cdots$
Confidence	-0.109***	-0.095**	-0.065	-0.288*	-0.194**
	(0.039)	(0.042)	(0.051)	(0.146)	(0.092)
Constant	1.166***	1.089***		0.978**	1.074***
	(0.153)	(0.167)		(0.436)	(0.324)
Observations	1,575	1,575	1,575	75	316
R-squared	0.005		0.001	0.051	0.014
Hausman test p-value	–	0.296		–	–

Notes: The dependent variable is the deviation from each post-shock theoretical price, $P_{it} - \bar{P}_t^*$ across i, where P_{it} and $\bar{P}_t^*$ represent the price set by subject i in period t and the theoretical price in period t, respectively. The variable *Confidence* takes an integer from one to six, where larger values indicate higher confidence in subject i's belief about the average price of the other subjects. The treatment is that of strategic complementarity ($\zeta = 0.5$). The sample is drawn only when $t \geq 16$ and either subject's own price or subject's group average price does not equal equilibrium. The last column shows the result of pooled estimation for the sample of $t = 16, 31, \cdots$. Figures in parentheses indicate the standard errors. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

in Assenza et al. (2014) had to discover the new equilibrium price on their own. Without a clearly defined target, those subjects might rely more heavily on adaptive expectations, which in turn can lead to oscillations. By contrast, the provision of a clear target equilibrium in our setting encourages participants to adopt a more forward-looking behavior, thereby eliminating oscillations. This result might have policy implications regarding information provision by the government and central bank in stabilizing business cycles.

3.3. *Causes of price stickiness*

3.3.1. *Strategic uncertainty*

Let us consider why a significant fraction of subjects choose a higher price than the best response to the stated average price of the others, especially after negative cost shocks when the prices are strategic complements. Unfortunately we are unable to make a precise assessment as to whether each subject's choice maximizes their expected payoff, since it must be derived from their subjective *distribution* of the other subjects' average price, which we are unable to elicit accurately. However, each subject's degree of confidence in the average price of the other subjects may well be a reasonable proxy for the level of subjective uncertainty about the other subjects' strategies. As we noted earlier, in every period, each subject stated the degree of confidence in their belief about the average price of the other subjects, in the integer scale of one to six, where larger values indicate higher confidence.

Table 4 examines the relationship between the level of confidence and the deviation from best response after negative cost shocks for the treatment with strategic complementarity. We use the data only for $t \geq 16$, where either the subject's own price or the group's average price deviates from the theoretical price. In other words, we focus on the groups that have not reached an equilibrium, which might give rise to a selection bias. However, it is important to note that our analysis includes all subjects within these groups, regardless of their level of rationality or confidence in their decisions. We employ the pooled, random-effect, and fixed-effect estimations for subject heterogeneity.

Let us focus on the left three columns of Table 4. We see that in all regressions, the coefficient on confidence is negative. The coefficient is significantly negative in the random-effect estimation as well as the pooled estimation, while the random-effect estimation is supported over the fixed-effect estimation according to the Hausman test. Together with our earlier observation in Fig. 2, the negative coefficient indicates that after negative cost shocks, uncertainty (low confidence) about the other subjects' average price leads to a higher price than the best response with respect to their beliefs. In other words, individual price adjustments are slower under strategic uncertainty after negative cost shocks when there is more strategic uncertainty. We do not obtain statistically significant association between uncertainty and pricing for positive cost shocks.

Table 5 shows that not only prices but also beliefs are correlated with confidence. We regress changes in beliefs of each subject in period t on their confidence. In order to highlight changes in beliefs, we only use the data from $t = 16, 31, 36, 41, 46, 51$, and 56, when shocks occur. While the Hausman test supports the fixed-effect estimation, the coefficients on confidence are all significant. We see that when the theoretical price decreases (increases), the coefficients are all negative (positive). This suggests that uncertainty about the average price of the other subjects leads to a smaller adjustment of beliefs under strategic complementarity for both types of shocks.

3.3.2. *Payoff structure*

Given our observation that uncertainty leads to slow adjustment of beliefs and pricing for both types of shocks, we now need to address why uncertainty is associated with an upward bias in pricing (relative to the best response) specifically after negative cost shocks. We propose that this is related to the payoff structure.

Consider Table 2 that exhibits strategic complementarity. Suppose that the theoretical price falls from 15 to 7, so that a switch to the payoff table represents a negative cost shock. One notable feature of the payoff structure is that choosing a price lower than the best response can give rise to disproportionately low, potentially negative payoffs, while a price higher than the best repose typically

Table 5
Regression of Change in Beliefs.

	Negative cost			Positive cost		
	Pooled	Random effects	Fixed effects	Pooled	Random effects	Fixed effects
Confidence	-0.487***	-0.654***	-0.811***	0.215**	0.250***	0.346***
	(0.104)	(0.107)	(0.13)	(0.085)	(0.09)	(0.119)
Constant	-4.012***	-3.461***		5.380***	5.223***	
	(0.366)	(0.404)		(0.346)	(0.38)	
Observations	225	225	225	210	210	210
R-squared	0.090		0.202	0.030		0.055
Hausman test p-value	–	0.000			0.000	

Notes: The dependent variable is the change in beliefs for subject i in period t, where t is 16, 31, 36, 41, 46, 51, or 56 when shocks occur. The variable *Confidence* takes an integer from one to six, where larger values indicate higher confidence in subject i's belief about the average price of the other subjects. The treatment is that of strategic complementarity ($\zeta = 0.5$). Figures in parentheses indicate the standard errors. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

leads to only mildly lower payoffs that can never be negative. This is because, in the price setting game, the worst possible outcome from charging an excessively high price is zero profit (such a firm simply does not produce given no demand), while an excessively low price than others can lead to a substantial loss by selling a large quantity at the price below the marginal cost.[13]

Due to the asymmetry in the payoff table, after a negative cost shock, if the average price of the other subjects is the previous theoretical price of 15 or slightly lower (such as 14, 13 or 12), a price lower than or equal to 7 may lead to the lowest possible payoff of −10. In other words, adjusting the price to the theoretical price faster than others can be "penalized" heavily. This may lead subjects to adjust their beliefs and prices slowly.[14]

To understand the effect of strategic uncertainty regarding beliefs about others' prices, suppose that a subject believes that the average price of the others is 9 with probability 1/3, 10 with probability 1/3, 11 with probability 1/6, and 12 with probability 1/6. The expected average price of the others is then 10.16, so that such an agent would have reported that he thinks the average price of the others is 10 (perhaps with a low confidence level). According to the payoff table, the best response is 8 when the average price of the others is 10, but given the subjective probability distribution, the expected payoff is higher when the subject chooses the price of 9, one unit higher than the best response on the payoff table.[15] For even higher average prices of the others, the disproportionately large losses when a subject's own price is low may look salient on the profit table, and this would further add to the upward bias in pricing even if they assign low likelihood to high prices of the others. Naturally, if subjects are aware that others are also subject to the upward bias, they would adjust their belief upwards that would also result in slow adjustment.

The profit table for the theoretical price of 15 shows the same type of asymmetry: payoffs drop more when the price is set below the best-response level than when it is set above. However, since the shocks induce an upward shift in the theoretical price, the "penalty" from adjusting the price to the equilibrium faster (i.e. setting a higher price) than others is relatively small. Thus adjustment towards the new theoretical price would not look as risky as otherwise, even if a subject is uncertain about the average price of the others. This should weaken the association between strategic uncertainty and the speed of price adjustments, and lead to aggregate price adjustments faster than those after negative cost shocks.

The effect of a faster adjustment to the new equilibrium price than others on individual profits is closely related to the absence of stickiness in the treatments under strategic substitutability. In the payoff tables for those treatments, a faster adjustment to the equilibrium price is rewarded rather than penalized, since by construction the best response to the average price of the others when it is higher (lower) than the equilibrium price is to set a price lower (higher) and closer to the equilibrium price than the average price. As a result, regardless of the subjective distribution of the price of the others, the profit maximizing strategy typically is to set the price equal to the new equilibrium price or in its neighborhood, which accelerates the transition to the new equilibrium in the aggregate.

3.3.3. Payoff (A) symmetry

We have seen so far that the marked price stickiness is observed only after negative cost shocks under strategic complementarity. We have argued that this is because of strategic uncertainty and the specific payoff structure. While the asymmetric payoff structure is not restrictive—being inherent in the conventional demand curve derived from the CES utility function—it is important to investigate whether this particular feature of the payoff structure, in conjunction with strategic complementarity, accounts for the observed stickiness.

We ran two additional treatments with modified profit tables with strategic complementarity but without the type of payoff asymmetry featured in the main treatments. The additional treatments share identical profit tables and differ only in whether the first shock leads to the lower or higher theoretical price. Relevant parts of the profit tables are shown in Table 6. The equilibrium prices (7 and 15) and the equilibrium payoff (5 throughout) are all identical to those in the profit tables of the main treatments,

[13] We will discuss this feature of the payoff table later in Section 4.

[14] A similar asymmetry is present in the payoff tables used in the nominal treatments of Fehr and Tyran (2001, 2008). This suggests that price stickiness can be attributed not only to money illusion but also to payoff asymmetry.

[15] The expected payoff given the subjective probability distribution is 6.280 when the subject's price is 8, and 6.594 when it is 9.

Table 6
Symmetric Profit Tables.

The average price of the other firms in your group

Your price	4	5	6	7	8	9	10	11	12	13	14	15
4	5.000	4.000	3.000	2.000	3.000	2.000	3.000	2.000	3.000	2.000	3.000	4.000
5	6.000	5.000	4.000	3.000	4.000	3.000	4.000	3.000	4.000	3.000	4.000	5.000
6	5.000	6.000	5.000	4.000	5.000	4.000	5.000	4.000	5.000	4.000	5.000	6.000
7	4.000	5.000	6.000	5.000	6.000	5.000	6.000	5.000	6.000	5.000	6.000	7.000
8	3.000	4.000	5.000	4.000	5.000	6.000	7.000	6.000	7.000	6.000	7.000	8.000
9	2.000	3.000	4.000	3.000	4.000	5.000	6.000	7.000	8.000	7.000	8.000	9.000
10	1.000	2.000	3.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10
11	0	1.000	2.000	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000
12	-1.000	0	1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000
13	-2.000	-1.000	0	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000
14	-3.000	-2.000	-1.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000
15	-4.000	-3.000	-2.000	-3.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000

Your price	7	8	9	10	11	12	13	14	15	16	17	18
7	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-3.000	-2.000	-3.000	-2.000
8	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-1.000	-2.000	-1.000
9	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	0	-1.000	0
10	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	1.000	0	1.000
11	7.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	2.000	1.000	2.000
12	6.000	7.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	3.000	2.000	3.000
13	5.000	6.000	7.000	6.000	7.000	6.000	5.000	4.000	3.000	4.000	3.000	4.000
14	4.000	5.000	6.000	5.000	6.000	5.000	6.000	5.000	4.000	5.000	4.000	5.000
15	3.000	4.000	5.000	4.000	5.000	4.000	5.000	6.000	5.000	6.000	5.000	6.000
16	2.000	3.000	4.000	3.000	4.000	3.000	4.000	5.000	4.000	5.000	6.000	7.000
17	1.000	2.000	3.000	2.000	3.000	2.000	3.000	4.000	3.000	4.000	5.000	6.000
18	0	1.000	2.000	1.000	2.000	1.000	2.000	3.000	2.000	3.000	4.000	5.000

Notes: We magnify a relevant part of the profit tables. The equilibrium prices are 7 and 15 in the top and bottom tables, respectively. The full tables are provided in the Online Appendix.

although the theoretical price of 4 also appears unintentionally. Also, each profit-maximizing price (shaded on the tables) given the average price of the other subjects is equal to a corresponding profit-maximizing price in the profit tables of the main treatments, which preserves strategic complementarity. However, the profits below and above each best response are symmetric with respect to a subject's own price, which implies that setting a lower price than the best response given an average price of the others does not lead to disproportionately low payoffs relative to cases where a subject sets a higher price than the best response. As a result, on the payoff tables, adjusting the price to the new (low or high) theoretical price faster than others does not lead to a large loss either.[16] We kept the other features of the profit tables as similar as possible to those in the main treatments.

Fig. 4 shows the change in the aggregate price in response to the shocks. We can immediately see that price stickiness almost disappears in the treatments with symmetric payoffs. After the first negative cost shock, the deviation from the theoretical price is positive and significantly different from zero at the ten percent level only for $t = 16, 17$ and 18. Likewise, after the first positive cost shock, the deviation from the theoretical price is negative and significantly different from zero at the ten percent level also for $t = 16, 17$ and 18. Unlike the treatments whose payoff tables are drawn from the price setting game, the level of deviation from the respective theoretical price is similar between both types of shocks. That is, price stickiness is not pronounced under a symmetric payoff structure that exhibits strategic complementarity.

To summarize, we find a sharp contrast between the price adjustments for the price setting game and those for the payoff tables based on symmetric payoffs. From this, together with our earlier discussion in Sections 3.3.1 and 3.3.2, we conclude that the stickiness observed in our experiment arises from the combination of three factors, namely i) strategic uncertainty; ii) strategic complementarity; and iii) asymmetric payoff structure that heavily penalizes faster adjustment to the equilibrium than other subjects.

In the Online Appendix, we discuss two types of quantification for the effect of strategic uncertainty, namely quantal response equilibrium, and individual pricing based on the belief that the others do not necessarily adjust their prices in every period.

3.4. Realized payoffs

Let us conclude our analysis of the main treatments with Table 7, which compares the actual profits the subjects earned and the hypothetical profits under four alternative strategies. We calculate the difference between the actual profits the subjects earned and the hypothetical profits, namely the mean of $\Pi^*_{it} - \Pi_{it}$ across i's, where Π^*_{it} and Π_{it} represent the hypothetical profit of subject i in period $t = 16$ and the actual profit of subject i in period $t = 16$, respectively.

[16] After a negative cost shock, adjusting the price to the equilibrium faster than others leads to a weakly larger profit.

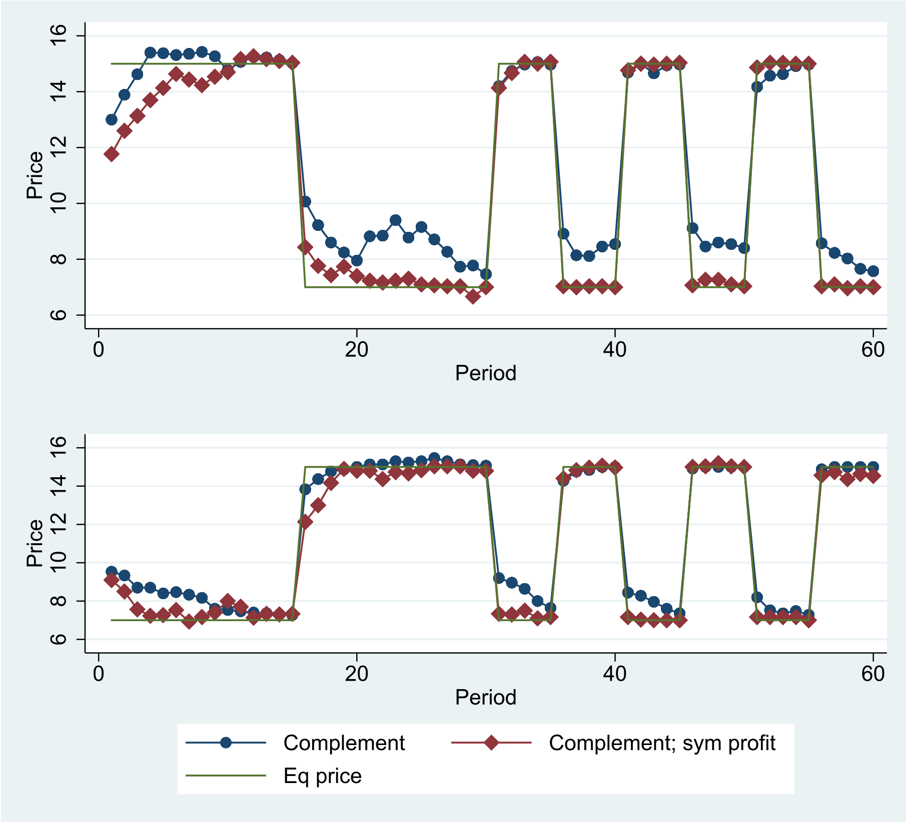


Fig. 4. Evolution of Average Prices (Asymmetric vs Symmetric Profits).

Table 7
Changes in Profits when Subjects Choose Different Prices after the First Shock.

	Complement		Substitute	
	Cost decrease	Cost increase	Cost decrease	Cost increase
If price is set by				
(i) Optimal price	2.47***	1.48***	1.74***	0.38**
(ii) Equilibrium	−5.53***	1.41***	1.74***	0.32
(iii) Old equilibrium	−3.28***	−13.63***	−5.49***	−15.09***
(iv) Optimal adaptive (level 1)	−1.54***	−13.36***	−4.63***	−2.36***
(v) Level 2	1.90***	−3.77***	−3.13***	−7.13***
(vi) Level 3	1.49**	0.28	0.13	−0.67***
(vii) Level 4	−5.53***	1.43***	1.74***	0.10

Notes: Changes in profits are the mean of $\Pi^*_{it} - \Pi_{it}$ across i, where Π_{it} and Π^*_{it} represent the profit of subject i in period $t = 16$ and the hypothetical profit of subject i in period $t = 16$, respectively. *Optimal price* is the price that maximizes Π^*_{it} that is calculated using ex post information on the average price of the other subjects. *Equilibrium* indicates the theoretical price in period t, while *Old equilibrium* indicates the theoretical price before costs change. *Optimal adaptive (level 1)* represents the price that maximizes Π^*_{it} under the assumption that the average price of the other subjects does not change from that in the previous period. *Level k)* represents the price that maximizes Π^*_{it} under the assumption that the average price of the other subjects equals the average of optimal adaptive prices of level $k-1$. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

The seven strategies of each subject considered in Table 7 are as follows: (i) the price that maximizes Π^*_{it} given the actual average price of the other subjects we observe ex post. In other words, P_{it} is given by the best response of subject i in period t to $\bar{P}_{it}$ to maximize $\Pi^*_{it}(P_{it}, \bar{P}_{it})$; (ii) the theoretical price in period t, i.e., $P_{it} = 7$ or 15; (iii) the old theoretical price, that is, the theoretical price before a shock; (iv) the optimal adaptive price that maximizes Π^*_{it} given the adaptive belief such that the average price of the other subjects is the same as that in period $t = 15$ (level-1 strategy). In this case, P_{it} is given by the best response of subject i in period t to $\bar{P}_{it-1}$ to maximize $\Pi^*_{it}(P_{it}, \bar{P}_{it-1})$; And (v) to (vii) the level-k for $k = 2, 3, 4$ strategy prices that maximize Π^*_{it} assuming the average price of others is determined by level-$(k-1)$ strategy. In other words, when we denote $P^{(k)}_{it}$ as the level-k price for subject i in period

t, $P_{it}^{(k)}$ is given by the best response of subject i in period t to the average price of others with level-k strategy, $\bar{P}_{it}^{(k-1)}$, to maximize $\Pi_{it}^{*}(P_{it}, \bar{P}_{it}^{(k-1)})$. The positive (negative) sign of the mean of $\Pi_{it}^{*} - \Pi_{it}$ indicates that subjects on average would have earned more (less) by choosing a different price. By construction, the mean of $\Pi_{it}^{*} - \Pi_{it}$ for (i) is non-negative.

Let us focus on the treatment under strategic complementarity where the first shock the subjects face is a negative cost shock (the first column in the table), since this is the case where considerable price stickiness is observed. The negative sign of the mean of $\Pi_{it}^{*} - \Pi_{it}$ for the case where (ii) they had instantaneously revised their prices to the new theoretical price indicates that subjects would have earned much smaller profits by doing so. In this regard, subjects' small deviation from the theoretical price is individually beneficial for them. Moreover, subjects would also have earned lower profits if (iii) they had not revised their prices at all. The negative sign for the case (iv) where they adopt the adaptive belief suggests that the subjects' adjustment of their beliefs, along with the corresponding prices, also paid off.[17] Finally, among the different levels of reasoning considered in cases (iv) to (vii), we find that the level-3 strategy most closely explains actual profits (i.e., $\Pi_{it}^{*} - \Pi_{it}$ is closest to zero). Overall, we see that the subjects' choice under significant price stickiness is reasonable at the individual level, compared to the other benchmark choices.

Interestingly, except for the case where prices are strategic complements and the first shock is a negative cost shock, choosing the theoretical price immediately after the first shock would have yielded higher profits than the observed prices did. In the second to the fourth columns of Table 7, the mean of $\Pi_{it}^{*} - \Pi_{it}$ under (ii) is positive and of almost the same size as that under (i). This suggests that despite the small overall deviation, the theoretical price was focal at least among sophisticated subjects.

4. Concluding remarks

This paper presents an attempt to disentangle potential sources of price stickiness in a controlled laboratory experiment. Our design involves no explicit friction, no uncertainty in fundamentals, no real-nominal distinction (hence no room for money illusion), or no need to calculate the best response given the belief about the other subjects prices. When we use payoffs derived from a price setting game with the demand from a CES utility function, we observe significant price stickiness only after negative cost shocks under strategic complementarity. Since stickiness disappears when the equilibrium payoffs and best response prices are the same but the payoffs are symmetric with respect to higher or lower price than the best response, we argue that the observed price stickiness should be attributed to the skewed payoff structure. Moreover, our findings suggest that the observed stickiness is caused by the presence of strategic uncertainty and a potentially large penalty from adjusting one's price to the new equilibrium faster than others.

The potential penalty from a faster adjustment to the lower theoretical price partially stems from the feature of the underlying model that setting a lower price than others may lead to a significant loss, which is equivalent to commitment to sales contracts even when the marginal cost becomes significantly higher than the price. In reality, firms may choose not to meet the demand when the posted price induces a loss-making quantity of demand, resulting in "sold out", so that the losses may not be as pronounced as in the payoff tables in our experiment. However, the penalty that leads to slower adjustments in beliefs and prices does not have to involve negative payoffs (losses) and our findings highlight the importance of the type of payoff asymmetry.

Our results may provide a useful insight into why many developing countries suffer from high and persistent inflation despite policymakers' efforts to curb it: downward price rigidity against negative cost shocks has been observed in many markets. In contrast, Japan has experienced extremely low inflation (and deflation especially before the Covid-19 pandemic), while the Bank of Japan has attempted to achieve 2% inflation. Surveys conducted in Japan show that Japanese firms have been reluctant to set a higher markup because they fear losing consumers, even when they are fully aware that the costs (wages, energy, materials, etc.) of their competitors have also increased. While this paper does not directly offer an explanation for upward rigidity, we may postulate that the competitive environment in many markets in Japan may have been such that adjusting the price "too fast" relative to competitors leads to a significant loss when a shock increases the theoretical price.

This paper's findings also suggest that there could be a unifying theoretical framework to study both upward and downward price rigidity systematically. Developing a dynamic model of imperfect price competition where strategic uncertainty may bias price setting upward or downward depending on the circumstances through firms' subjective beliefs about their competitors' pricing would be an interesting future research agenda.

Appendix A. Experimental instructions and payoff tables

Instructions

Thank you for participating in today's experiment.

You are participating in an experiment related to decision making. After reading the experimental instructions, you will make decisions to earn real money. Other participants will not know your identity, your decisions, or the amount of money you earn.

Please do not talk during the experiment. If you have any questions, please raise your hand. Also, please do not place anything on the desk, including cell phones or writing instruments. Instead, please store them in your bag or elsewhere.

[17] The old theoretical price and the best response to the adaptive belief may differ for individual subjects even if the average price across groups converges to the theoretical price by $t = 15$, since groups within a treatment may reach different prices at $t = 15$.

During the experiment, you will play the role of a company selling a product. The company determines the selling price of the product for each period. Your company's profit will be determined based on the prices selected by your company and by other companies.

There are 30 experiment participants. These participants have been divided into 6 groups of 5. Accordingly, the group you are in has 4 other members; you will not know their identities. Furthermore, the groups will remain the same throughout the experiment.

During each period of the experiment, all companies will determine the selling price of their products at the same time. Prices can range between (and including) the numbers 1 and 20.

The profit that your company will earn will depend on the price that you have chosen, as well as the average price that the 4 other companies in your group have chosen. The average price will be calculated based on the following formula. Average price = (sum of prices chosen by the 4 other companies) ÷4 The resulting average price will also be between 1 and 20, inclusive. Furthermore, if the result is a decimal value, the average price will be the calculated as the closest number value between 1 and 20, inclusive. In the event that there are two equally close number values, the higher value will be used as the average price.

In addition, if you change your selling price from the price in the previous period, a 0.1 price revision fee will be deducted from the profit earned by your company. If your price does not change, then there will be no fee. However, a required 0.1 fee will be deducted during the first period.

How to Read the Profit Table: The profit table on the next page is an example of the one that will be distributed (Fig. 1). However, for simplicity, the only prices option used in the example are numbers between 1 and 5, inclusive. This profit table shows the profit that will be earned by your company once your selling price and the average price have been determined.

(Figure 1) Profit Table

		Average price of other companies in your group				
		1	2	3	4	5
Your price	1	1.00	1.00	0.00	−3.00	−5.00
	2	2.00	4.00	3.00	−1.00	−3.00
	3	0.00	5.00	6.00	3.00	0.00
	4	0.00	2.00	8.00	10.00	6.00
	5	0.00	0.00	2.00	6.00	5.00

(Note) The gray cells indicate the maximum profit that can be earned in each column.

For example, let's suppose that you select a price of 2 and the average price is 3. In this case, your company would earn a profit of 3.00.

If the price you select is much higher than the average price of the other companies, your company's product will not sell. Accordingly, you will have zero sales and zero profit. Conversely, if the price you select is much lower than the average price of the other companies, then your company will have considerable sales. However, please use caution. If your price is too low, then costs will exceed revenues and you will have a negative profit. For example, if you select a price of 2 and the average price is 5, then the profit earned by your company will be -3.00.

When selecting a price, you will not know the value of average price selected by the other 4 companies. As a result, the profit table is useful for calculating your profit based on your prediction of what the other 4 companies will select as an average price.

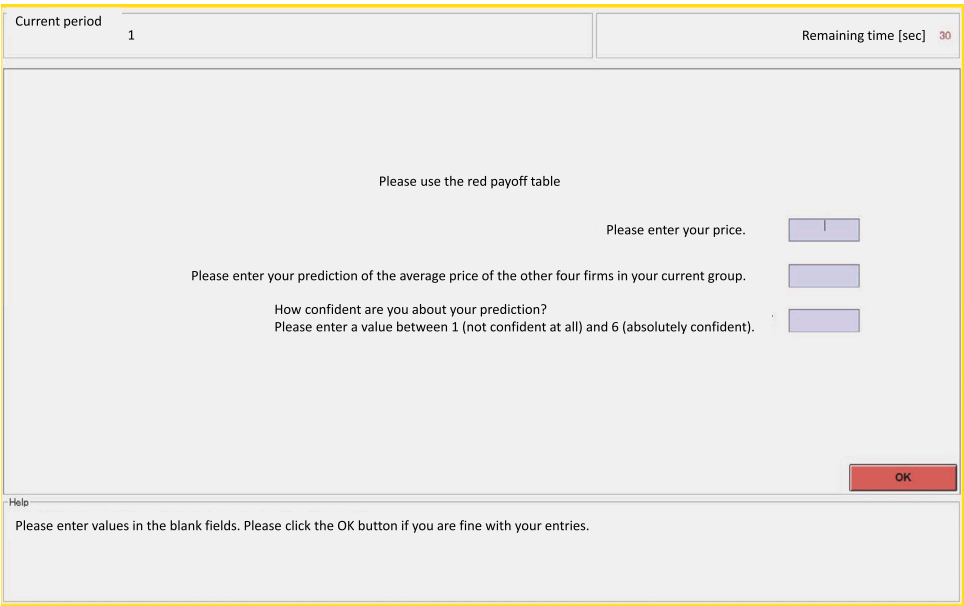
For example, let us suppose you predict that the average price will be 4. In this case, if you select a price of 2, then the predicted value of the profit earned by your company will be -1.00.

In order to confirm your understanding of the game, please answer the practice question on the screen. It does not matter how many times you enter a wrong answer here, as the experiment will not begin until all participants answer the question correctly.

The profit table used here is to explain the experiment. A sheet of paper with a different profit table will be distributed for the actual experiment.

Computer Screen Display: Fig. 2 is the input screen. The current period is shown in the upper left and the amount of time left to select a price is shown in the upper right.

(Figure 2) Input Screen



Please input values into each of the three input cells in the middle of the screen.

(Determine a price) Please select a number value between 1 and 20, inclusive, for the first cell.

(Expected value of the average price selected by the 4 other companies) In the second cell, please select a number between 1 and 20, inclusive, as your prediction of the average price. This choice will not affect your profit or be known by the other companies. Your profit will be determined based on the actual average price. The predicted average price will be useful in determining your own price, so please answer as accurately as possible.

(Confidence) In the third cell, please select a number between 1 and 6, inclusive, to indicate your confidence in the predicted average price you input in the second cell.

1: I have no confidence that my prediction is correct.

2: I have very little confidence that my prediction is correct.

3: I have little confidence that my prediction is correct.

4: I have some confidence that my prediction is correct.

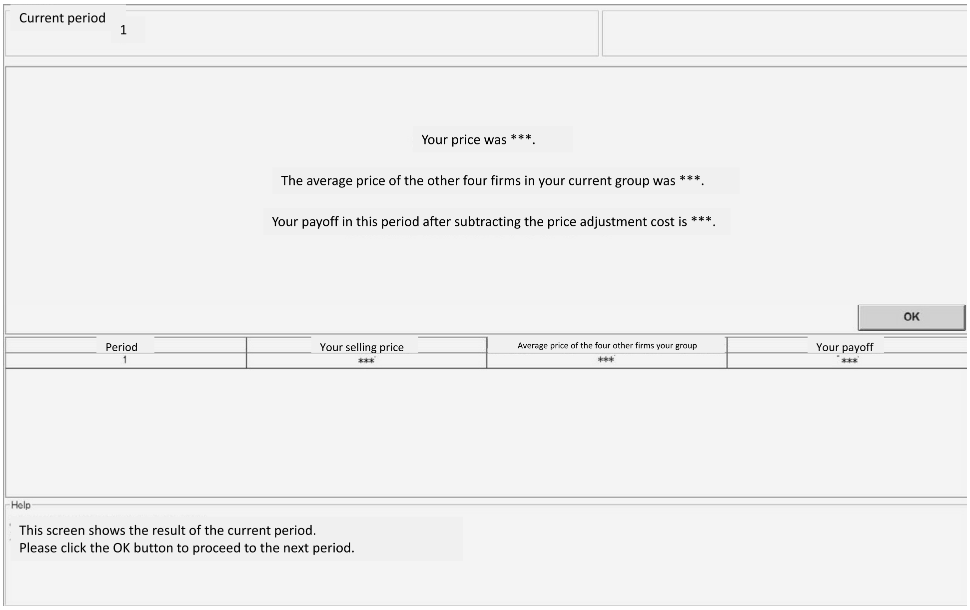
5: I am confident that my prediction is correct.

6: I am absolutely confident that my prediction is correct.

After you have completed all 3 cells, please click on the OK button. After you have clicked this button once, it will not be possible to change your decisions for the period.

Once all companies have selected their prices, the screen will display the results of that period (Fig. 3). The current period is shown in the upper left, while the remaining results display time is shown in the upper right.

(Figure 3) Results Display Screen



In the results display screen, the selling price you selected during that period, the actual average price, and the profit that your company obtained are displayed. If you changed your selling price from the previous period, a price revision fee of 0.1 will be deducted from your profit. When you are ready to proceed, please click on the OK button.

Distribution of the Profit Table: Two different profit tables for use in the actual experiment will be distributed. The experiment session lasts for more than 30 periods. For the initial 15 periods (periods 1 to 15), please use the red profit table. For the next 15 periods (periods 16 to 30), please use the blue profit table. After this, please alternate use of the red and blue profit tables every 5 periods. In other words, for periods 31 to 35, please use the red profit table. Also, please note that identical profit tables will be distributed to all members of the same group.

The gray cells indicate the price that will earn the maximum profit in each column. Also, the profit for each period is set at a maximum value of 10 and a minimum value of (-10).

Calculating Your Reward: After the experiment is over, your reward will be determined as follows. Five periods will be randomly selected, and the profit earned by your company during those periods will be averaged and then converted to cash at the following rate.

1 point = 200 JPY A 1,000 JPY experiment participation payment will be added to this and the total paid to you.

Do you have any questions? If you have any questions during the experiment, please raise your hand to let us know.

Profit Tables[18]

The average price of the other firms in your group

Your price	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-5.929	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
2	-0.015	-2.728	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
3	0.006	-0.020	-1.310	-9.633	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
4	0.002	0.035	0.063	-0.465	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
5	0	0.020	0.094	0.206	5.000	-8.186	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
6	0	0.010	0.058	0.179	10	5.000	2.247	-2.819	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
7	0	0.005	0.033	0.114	10	5.053	5.000	5.011	4.092	1.209	-5.009	-10	-10	-10	-10	-10	-10	-10	-10	-10
8	0	0.003	0.020	0.071	8.254	3.646	4.088	5.000	5.987	6.720	6.761	5.506	2.139	-4.405	-10	-10	-10	-10	-10	-10
9	0	0.002	0.012	0.045	5.380	2.478	2.926	3.823	5.000	6.361	7.779	9.060	9.927	9.996	8.764	5.585	-0.351	-10	-10	-10
10	0	0.001	0.008	0.029	3.554	1.678	2.038	2.753	3.745	5.000	6.496	8.187	9.990	10	10	10	10	10	10	7.034
11	0	0	0.005	0.019	2.399	1.151	1.424	1.961	2.728	3.736	5.000	6.524	8.300	10	10	10	10	10	10	10
12	0	0	0.003	0.013	1.656	0.804	1.006	1.405	1.983	2.759	3.757	5.000	6.504	8.277	10	10	10	10	10	10
13	0	0	0.002	0.009	1.168	0.572	0.723	1.019	1.452	2.042	2.814	3.792	5.000	6.460	8.188	10	10	10	10	10
14	0	0	0.002	0.007	0.841	0.415	0.528	0.749	1.075	1.524	2.117	2.878	3.831	5.000	6.406	8.070	10	10	10	10
15	0	0	0.001	0.005	0.617	0.306	0.391	0.558	0.806	1.150	1.607	2.199	2.947	3.873	5.000	6.350	7.942	9.797	10	10
16	0	0	0	0.004	0.460	0.229	0.294	0.422	0.612	0.877	1.232	1.694	2.282	3.015	3.914	5.000	6.293	7.813	9.580	10
17	0	0	0	0.003	0.349	0.174	0.225	0.323	0.471	0.677	0.954	1.317	1.781	2.363	3.082	3.954	5.000	6.238	7.688	9.368
18	0	0	0	0.002	0.268	0.134	0.174	0.251	0.366	0.528	0.747	1.034	1.403	1.867	2.443	3.146	3.993	5.000	6.186	7.568
19	0	0	0	0.002	0.209	0.105	0.136	0.196	0.288	0.416	0.590	0.819	1.114	1.488	1.952	2.520	3.208	4.029	5.000	6.137
20	0	0	0	0.001	0.164	0.083	0.107	0.156	0.228	0.331	0.471	0.655	0.893	1.195	1.571	2.033	2.594	3.266	4.063	5.000

Note: The cell in gray indicates the maximum profit in each column.

(a) Strategic complementarity: $P^* = 7$

The average price of the other firms in your group

Your price	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
2	-0.095	-6.388	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
3	-0.002	-0.341	-4.298	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
4	0	-0.022	-0.468	-3.053	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
5	0	0.005	-0.045	-0.473	-2.202	-7.191	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
6	0	0.005	0.011	-0.049	-0.403	-1.575	-4.543	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
7	0	0.003	0.015	0.024	-0.027	-0.294	-1.087	-2.939	-6.683	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
8	0	0.002	0.011	0.030	0.048	0.016	-0.167	-0.694	-1.873	-4.169	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
9	0	0.001	0.008	0.025	0.053	0.081	0.076	-0.034	-0.368	-1.116	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
10	0	0	0.005	0.018	0.044	0.082	0.124	0.146	0.099	-0.093	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
11	0	0	0.004	0.013	0.033	0.068	0.118	0.175	0.223	0.230	5.000	-1.581	-6.029	-10	-10	-10	-10	-10	-10	-10
12	0	0	0.003	0.010	0.025	0.054	0.098	0.159	0.231	0.304	10	5.000	2.253	-0.336	-3.588	-7.971	-10	-10	-10	-10
13	0	0	0.002	0.007	0.019	0.041	0.078	0.132	0.204	0.292	10	6.766	5.000	3.796	2.453	0.646	-1.887	-5.411	-10	-10
14	0	0	0.001	0.005	0.014	0.032	0.061	0.106	0.170	0.253	10	6.692	5.517	5.000	4.568	3.990	3.100	1.742	-0.253	-3.075
15	0	0	0.001	0.004	0.011	0.024	0.048	0.085	0.138	0.211	10	5.981	5.175	5.002	5.000	5.001	4.898	4.596	3.997	2.988
16	0	0	0	0.003	0.008	0.019	0.037	0.067	0.112	0.173	8.854	5.117	4.551	4.548	4.739	5.000	5.259	5.459	5.540	5.438
17	0	0	0	0.002	0.006	0.015	0.030	0.054	0.090	0.141	7.311	4.291	3.885	3.962	4.228	4.591	5.000	5.420	5.816	6.149
18	0	0	0	0.002	0.005	0.012	0.023	0.043	0.072	0.115	6.010	3.567	3.269	3.380	3.664	4.049	4.502	5.000	5.522	6.045
19	0	0	0	0.001	0.004	0.009	0.019	0.034	0.059	0.094	4.939	2.955	2.733	2.854	3.128	3.500	3.945	4.449	5.000	5.586
20	0	0	0	0.001	0.003	0.007	0.015	0.028	0.048	0.077	4.067	2.450	2.281	2.400	2.652	2.993	3.407	3.883	4.416	5.000

Note: The cell in gray indicates the maximum profit in each column.

(b) Strategic complementarity, $P^* = 15$

The average price of the other firms in your group

Your price	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
2	-1.049	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
3	-0.085	-1.737	-9.851	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
4	-0.014	-0.270	-1.457	-4.646	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	10	10	10	10	10	10
5	-0.003	-0.061	-0.304	-0.890	-1.902	-3.237	-10	-10	-6.374	7.468	10	10	10	10	10	10	10	10	10	10
6	-0.001	-0.017	-0.076	-0.188	-0.302	-0.251	1.801	6.002	10	10	10	10	10	10	10	10	10	10	10	10
7	0	-0.005	-0.020	-0.031	0.013	0.231	5.000	6.761	10	10	10	10	10	10	10	10	10	10	10	10
8	0	-0.002	-0.004	0.006	0.065	0.252	4.167	5.000	7.507	10	10	10	10	10	10	10	10	10	10	10
9	0	0	0	0.012	0.062	0.197	3.004	3.436	5.000	7.571	10	10	10	10	10	10	10	10	10	10
10	0	0	0.001	0.012	0.048	0.144	2.101	2.341	3.346	5.000	7.462	10	10	10	10	10	10	10	10	10
11	0	0	0.001	0.009	0.036	0.103	1.471	1.613	2.278	3.374	5.000	7.311	10	10	10	10	10	10	10	10
12	0	0	0.001	0.007	0.027	0.074	1.041	1.129	1.582	2.329	3.434	5.000	7.156	10	10	10	10	10	10	10
13	0	0	0.001	0.006	0.020	0.054	0.749	0.805	1.122	1.643	2.413	3.503	5.000	7.010	9.657	10	10	10	10	10
14	0	0	0	0.004	0.015	0.040	0.547	0.585	0.811	1.183	1.732	2.508	3.573	5.000	6.877	9.306	10	10	10	10
15	0	0	0	0.003	0.011	0.030	0.406	0.432	0.596	0.868	1.268	1.832	2.605	3.640	5.000	6.758	8.997	10	10	10
16	0	0	0	0.003	0.008	0.022	0.306	0.324	0.446	0.647	0.944	1.362	1.933	2.698	3.703	5.000	6.651	8.725	10	10
17	0	0	0	0.002	0.007	0.017	0.233	0.246	0.339	0.490	0.714	1.028	1.459	2.034	2.788	3.762	5.000	6.555	8.485	10
18	0	0	0	0.002	0.005	0.013	0.180	0.190	0.260	0.377	0.548	0.788	1.116	1.555	2.131	2.873	3.816	5.000	6.469	8.271
19	0	0	0	0.001	0.004	0.010	0.141	0.148	0.203	0.293	0.426	0.612	0.866	1.205	1.650	2.224	2.952	3.866	5.000	6.391
20	0	0	0	0	0.003	0.008	0.112	0.117	0.160	0.231	0.335	0.481	0.680	0.946	1.294	1.743	2.312	3.027	3.913	5.000

Note: The cell in gray indicates the maximum profit in each column.

(c) Strategic substitutability, $P^* = 7$

The average price of the other firms in your group

Your price	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
2	-3.626	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
3	-0.311	-6.855	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
4	-0.054	-1.181	-7.105	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
5	-0.014	-0.299	-1.785	-6.293	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
6	-0.005	-0.097	-0.572	-1.998	-5.241	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
7	-0.002	-0.037	-0.216	-0.749	-1.946	-4.218	-8.070	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
8	0	-0.016	-0.092	-0.317	-0.814	-1.745	-3.301	-5.698	-9.165	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10	-10
9	0	-0.008	-0.043	-0.146	-0.372	-0.788	-1.470	-2.502	-3.965	-5.936	-8.481	-10	-10	-10	-10	-10	-10	-10	-10	-10
10	0	-0.004	-0.022	-0.073	-0.182	-0.380	-0.697	-1.166	-1.812	-2.655	-3.702	-4.946	-6.362	-10	-10	-10	-10	-10	-10	-10
11	0	-0.002	-0.012	-0.038	-0.094	-0.192	-0.346	-0.566	-0.856	-1.216	-1.635	-2.090	-2.543	-10	-10	-10	-9.609	-5.986	-1.792	3.439
12	0	-0.001	-0.006	-0.021	-0.050	-0.101	-0.177	-0.281	-0.409	-0.554	-0.700	-0.823	-0.887	-10	-3.815	-0.743	1.985	5.092	8.917	10
13	0	0	-0.004	-0.012	-0.028	-0.054	-0.092	-0.140	-0.192	-0.239	-0.266	-0.251	-0.164	0.450	2.360	4.000	5.983	8.497	10	10
14	0	0	-0.002	-0.007	-0.016	-0.030	-0.048	-0.068	-0.084	-0.087	-0.064	0.004	0.141	5.000	4.538	5.423	6.884	8.875	10	10
15	0	0	-0.001	-0.004	-0.009	-0.016	-0.024	-0.030	-0.029	-0.014	0.029	0.112	0.256	6.419	5.000	5.475	6.565	8.132	10	10
16	0	0	0	-0.003	-0.005	-0.009	-0.012	-0.011	-0.002	0.021	0.067	0.150	0.285	6.473	4.753	5.000	5.826	7.060	8.692	10
17	0	0	0	-0.002	-0.003	-0.004	-0.005	0	0.011	0.035	0.080	0.156	0.275	5.969	4.247	4.367	5.000	5.976	7.276	8.922
18	0	0	0	0	-0.002	-0.002	0	0.004	0.016	0.040	0.081	0.147	0.250	5.279	3.684	3.732	4.223	5.000	6.040	7.357
19	0	0	0	0	0	0	0.001	0.007	0.018	0.039	0.075	0.133	0.220	4.570	3.148	3.156	3.541	4.163	5.000	6.060
20	0	0	0	0	0	0	0.002	0.007	0.018	0.037	0.068	0.117	0.191	3.914	2.670	2.656	2.962	3.464	4.141	5.000

Note: The cell in gray indicates the maximum profit in each column.

(d) Strategic substitutability, $P^* = 15$

The average price of the other firms in your group

Your price	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	5.000	4.000	3.000	2.000	1.000	0	-1.000	0	-1.000	0	-1.000	0	-1.000	0	1.000	0	0	0	0	0
2	6.000	5.000	4.000	3.000	2.000	1.000	0	1.000	0	1.000	0	1.000	0	1.000	2.000	1.000	1.000	1.000	1.000	1.000
3	7.000	6.000	5.000	4.000	3.000	2.000	1.000	2.000	1.000	2.000	1.000	2.000	1.000	2.000	3.000	2.000	2.000	2.000	2.000	2.000
4	6.000	7.000	6.000	5.000	4.000	3.000	2.000	3.000	2.000	3.000	2.000	3.000	2.000	3.000	4.000	3.000	3.000	3.000	3.000	3.000
5	5.000	6.000	7.000	6.000	5.000	4.000	3.000	4.000	3.000	4.000	3.000	4.000	3.000	4.000	5.000	4.000	4.000	4.000	4.000	4.000
6	4.000	5.000	6.000	5.000	6.000	5.000	4.000	5.000	4.000	5.000	4.000	5.000	4.000	5.000	6.000	5.000	5.000	5.000	5.000	5.000
7	3.000	4.000	5.000	4.000	5.000	6.000	5.000	6.000	5.000	6.000	5.000	6.000	5.000	6.000	7.000	6.000	6.000	6.000	6.000	6.000
8	2.000	3.000	4.000	3.000	4.000	5.000	4.000	5.000	6.000	7.000	6.000	7.000	6.000	7.000	8.000	7.000	7.000	7.000	7.000	7.000
9	1.000	2.000	3.000	2.000	3.000	4.000	3.000	4.000	5.000	6.000	7.000	8.000	7.000	8.000	9.000	8.000	8.000	8.000	8.000	8.000
10	0	1.000	2.000	1.000	2.000	3.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10	9.000	9.000	9.000	9.000	9.000
11	-1.000	0	1.000	0	1.000	2.000	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10	10	10	10	10
12	-2.000	-1.000	0	-1.000	0	1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10	10	10	10
13	-3.000	-2.000	-1.000	-2.000	-1.000	0	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10	10	10
14	-4.000	-3.000	-2.000	-3.000	-2.000	-1.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10	10
15	-5.000	-4.000	-3.000	-4.000	-3.000	-2.000	-3.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10
16	-6.000	-5.000	-4.000	-5.000	-4.000	-3.000	-4.000	-3.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000
17	-7.000	-6.000	-5.000	-6.000	-5.000	-4.000	-5.000	-4.000	-3.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000
18	-8.000	-7.000	-6.000	-7.000	-6.000	-5.000	-6.000	-5.000	-4.000	-3.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000	7.000
19	-9.000	-8.000	-7.000	-8.000	-7.000	-6.000	-7.000	-6.000	-5.000	-4.000	-3.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000	6.000
20	-10	-9.000	-8.000	-9.000	-8.000	-7.000	-8.000	-7.000	-6.000	-5.000	-4.000	-3.000	-2.000	-1.000	0	1.000	2.000	3.000	4.000	5.000

Note: The cell in gray indicates the maximum profit in each column.

(e) Strategic complementarity and symmetric payoffs, $P^* = 7$

The average price of the other firms in your group

Your price	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-3.000	-4.000	-5.000	-6.000	-7.000	-8.000	-9.000	-8.000	-9.000	-8.000	-9.000	-8.000
2	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-3.000	-4.000	-5.000	-6.000	-7.000	-8.000	-7.000	-8.000	-7.000	-8.000	-7.000
3	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-3.000	-4.000	-5.000	-6.000	-7.000	-6.000	-7.000	-6.000	-7.000	-6.000
4	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-3.000	-4.000	-5.000	-6.000	-5.000	-6.000	-5.000	-6.000	-5.000
5	7.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-3.000	-4.000	-5.000	-4.000	-5.000	-4.000	-5.000	-4.000
6	6.000	9.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-3.000	-4.000	-3.000	-4.000	-3.000	-4.000	-3.000
7	5.000	8.000	9.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-3.000	-2.000	-3.000	-2.000	-3.000	-2.000
8	4.000	7.000	8.000	9.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	-2.000	-1.000	-2.000	-1.000	-2.000	-1.000
9	3.000	6.000	7.000	8.000	9.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	-1.000	0	-1.000	0	-1.000	0
10	2.000	5.000	6.000	7.000	8.000	7.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	0	1.000	0	1.000	0	1.000
11	1.000	4.000	5.000	6.000	7.000	6.000	7.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	1.000	2.000	1.000	2.000	1.000	2.000
12	0	3.000	4.000	5.000	6.000	5.000	6.000	7.000	8.000	7.000	6.000	5.000	4.000	3.000	2.000	3.000	2.000	3.000	2.000	3.000
13	-1.000	2.000	3.000	4.000	5.000	4.000	5.000	6.000	7.000	6.000	7.000	6.000	5.000	4.000	3.000	4.000	3.000	4.000	3.000	4.000
14	-2.000	1.000	2.000	3.000	4.000	3.000	4.000	5.000	6.000	5.000	6.000	5.000	6.000	5.000	4.000	5.000	4.000	5.000	4.000	5.000
15	-3.000	0	1.000	2.000	3.000	2.000	3.000	4.000	5.000	4.000	5.000	4.000	5.000	6.000	5.000	6.000	5.000	6.000	5.000	6.000
16	-4.000	-1.000	0	1.000	2.000	1.000	2.000	3.000	4.000	3.000	4.000	3.000	4.000	5.000	4.000	5.000	6.000	7.000	6.000	7.000
17	-5.000	-2.000	-1.000	0	1.000	0	1.000	2.000	3.000	2.000	3.000	2.000	3.000	4.000	3.000	4.000	5.000	6.000	7.000	8.000
18	-6.000	-3.000	-2.000	-1.000	0	-1.000	0	1.000	2.000	1.000	2.000	1.000	2.000	3.000	2.000	3.000	4.000	5.000	6.000	7.000
19	-7.000	-4.000	-3.000	-2.000	-1.000	-2.000	-1.000	0	1.000	0	1.000	0	1.000	2.000	1.000	2.000	3.000	4.000	5.000	6.000
20	-8.000	-5.000	-4.000	-3.000	-2.000	-3.000	-2.000	-1.000	0	-1.000	0	-1.000	0	1.000	0	1.000	2.000	3.000	4.000	5.000

Note: The cell in gray indicates the maximum profit in each column.

(f) Strategic complementarity and symmetric payoffs, $P^* = 15$

Appendix B. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jedc.2025.105186.

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[18] P^* below denotes the theoretical price for each case.

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