Crawford School of Public Policy

CAMA

Centre for Applied Macroeconomic Analysis

Price Stickiness and Strategic Uncertainty: An Experimental Study

CAMA Working Paper 63/2023
December 2023

Yukihiko Funaki
Waseda University

Kohei Kawamura
Waseda University

Nobuyuki Uto
Matsumoto University

Kozo Ueda
Waseda University
Centre for Applied Macroeconomic Analysis, ANU

Abstract

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. We argue that the observed downward stickiness can be attributed to the presence of strategic uncertainty and strategic complementarity, combined with an asymmetric payoff structure such that adjusting an individual price faster than others toward the lower equilibrium price can potentially lead to a significant loss, compared to faster adjustment to the higher equilibrium price.

Keywords

strategic complements; sticky prices; bounded rationality

JEL Classification

C92, E32, E52

Address for correspondence:

(E) cama.admin@anu.edu.au

ISSN 2206-0332

Price Stickiness and Strategic Uncertainty: An Experimental Study*

Yukihiko Funaki[†] Kohei Kawamura[‡] Nobuyuki Uto[§] Kozo Ueda[¶]

November 2023

Abstract

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. We argue that the observed downward stickiness can be attributed to the presence of strategic uncertainty and strategic complementarity, combined with an asymmetric payoff structure such that adjusting an individual price faster than others toward the lower equilibrium price can potentially lead to a significant loss, compared to faster adjustment to the higher equilibrium price.

Keywords: strategic complements; sticky prices; bounded rationality

JEL classification: C92, E32, E52

*We appreciate helpful comments from Marcus Giamattei, Nobuyuki Hanaki, Ed Hopkins, Yukio Koriyama, Tatiana Kornienko, Luba Petersen, and conference and seminar participants at the BEAM-ABEE Workshop (Amsterdam), International Workshop on Theoretical and Experimental Macroeconomics (Berlin), Kyoto University, SWET Workshop (Sapporo), the University of Tokyo, and Waseda University. This work was supported by JSPS Core-to-Core Program (Grant Number: JPJSCCA20200001) and JSPS KAKENHI (Grant Numbers: 17H02503, 18KK004, 22H00829). All errors are our own.

[†]Waseda University (funaki@waseda.jp)

[‡]Waseda University (kkawamura@waseda.jp)

[§]Matsumoto University (nobuyuki.uto@gmail.com)

[¶]Corresponding author. Waseda University and Centre for Applied Macroeconomic Analysis (CAMA, ANU) (kozo.ueda@waseda.jp).

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 for limited cognitive ability). 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 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 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 but not when they are strategic substitutes; and that the observed stickiness is primarily due to slow adjustment of subjects' beliefs about the others' prices, as consistent with the existing experimental literature. Unlike previous studies, however, we repeat both negative and positive cost push shocks, and we find that stickiness is much more pronounced after fully anticipated negative cost push shocks than positive cost push shocks, which points to downward rigidity.

We also find that the stickiness after negative cost push shocks is accompanied by slow adjustment of beliefs and mild tendency to set a price slightly above the best response to their stated beliefs. 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 are able to demonstrate that the 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 where strategic uncertainty (i.e. uncertainty regarding the other firms' prices) makes a faster adjustment to the equilibrium following a negative cost push shock disproportionately "risky" in the sense that the firm may incur a substantive loss in the adjustment process. In order to quantify this feature of the profit function under uncertainty in competitors' prices, we derive a quantal response equilibrium (QRE), which confirms that the distribution of the prices is biased upward and thus the price adjustment indeed tends to be smaller, when all firms are subject to making mistakes in a static environment. We also study the price adjustment dynamics in a model that combines the profit function and Calvo-type pricing where the firms believe that their competitors might not adjust their prices in every period. In the model we observe that the price adjustment is slower with negative cost push shocks under strategic complementarity, as consistent with our experimental findings. Overall,our main contribution is to show that price stickiness does not require explicit frictions in price adjustments, uncertainty in fundamentals, money illusion or cognitive limitations, but comes about in the presence of both strategic complementarity *and* a payoff structure such that strategic uncertainty works in the direction of slow adjustment. We also find that price stickiness becomes less pronounced as subjects experience more shocks, but does not disappear.

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) have identified the importance of the strategic environment in price stickiness. In a closely related setup, Petersen and Winn (2014) find that price stickiness is more strongly associated with difficulty in finding the payoff-maximizing price than money illusion. Unlike these earlier contributions, all variables in our experiments are in real terms, so that we rule out money illusion. Furthermore, our design eliminates concerns regarding cognitive limitations, by highlighting the profit-maximizing price given the other subjects' average price in payoff tables and by using the same payoff tables for every subject.

This paper is also related to recent experimental research on transition among efficient and inefficient equilibria in dynamic coordination games. Smerdon, Offerman, and Gneezy (2020), Andreoni, Nikiforakis, Siegenthaler (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 efficient equilibrium under various circumstances.[1] Smerdon, Offerman, and Gneezy (2020) and Andreoni, Nikiforakis, Siegenthaler (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 are 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, Kryvtsov, and Petersen (2011), 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.[2] Expectations-based New Keynesian models have also been tested experimentally.[3] These studies typically focus on the effect of policy intervention on forecasts/expectations in the presence of exogenous uncertainty. Lambsdorff, Schubert, and Giamattei (2013), Baeriswyl and Cornand (2014), Cornand and Heinemann (2014b) and Baeriswyl, Boun My and Cornand (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 behavioural determinants of price rigidity, such as cognitive

[1]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.

[2]See for example, Wilson (1998), Davis and Korenok (2011), Noussair, Pfajfar, and Zsiros (2015), and Magnani, Gorry, and Oprea (2016).

[3]Adam (2007), Assenza et al. (2013), Luhan and Scharler (2014), Noussair, Pfajfar, and Zsiros (2015), Kryvtsov and Petersen (2015), and Pfajfar and Zakelj (2016).

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, and the observed patterns of price adjustment cannot be systematically described by a cognitive hierarchy model.

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 push 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.[4]

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

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

[4]Angeletos, Huo and Sastry (2020) argue that professional forecasters' expectations of inflation under-react initially but over-shoot later on.

which leads to the profit-maximizing price

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

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).[5]

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).[6] 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.[7]

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 cost push shock leads to a higher equilibrium price corresponding to the high cost, and a negative cost push shock leads to a lower equilibrium 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 equilibrium price 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.

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 $t = 16, 31, 36, 41, 45, 51, 56,$

[5]In other words, $\partial^2 \Pi_{it} / \partial P_{it} \partial \bar{P}_{it}$ is positive (negative) when ζ is positive (negative).

[6]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.

[7]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 is 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 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	$P_{it} \in \{1, 2, \ldots, 20\}$
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	
Equilibrium price under cost decrease (Down)	$\bar{P}_t^* = 7$
Equilibrium 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.

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.[8] 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. 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.[9] 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 $\bar{P}_{it}$.

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

[8]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, Tremewan, and van der Weele (2015), and Charness, Gneezy, and Rasocha (2021) for insightful discussions on belief elicitation methods. In particular, Charness, Gneezy, and Rasocha (2021) note that non-incentivized responses "seem to do as well as rather complex incentivized methods".

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

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

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

Table 2: Profit Tables when Prices are Strategic Complements

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.

Petersen and Winn (2014) who gave different profit tables to subjects within the same group. Furthermore, in ours there was no need to consider any difference between real and nominal profits.

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 equilibrium price.[10] 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

[10]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 equilibrium price.

make some cells unnecessarily salient due to extremely large or small numbers.

The subjects received a show-up fee of 1,000 yen ($\approx$ 9.5USD 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.

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.

3 Experimental Results

3.1 Aggregate Price Movement

Let us first examine the movement of the market price. Figure 1 and Table 3 show how the price changes in response to shocks for each treatment. Figure 1 presents the evolution of the average price of all subjects, along with the equilibrium price. In all treatments we observe price stickiness after negative cost push shocks, particularly in the treatment with strategic complementarity. Interestingly, the presence of the menu cost hardly affects the price movement. If anything, the price tends to converge to the equilibrium price more smoothly.[11]

Table 3 records the magnitude of deviation from the equilibrium 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 equilibrium 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 considerably long duration after the first negative cost push shock. In contrast, both Table 3 and Figure 1 indicate that, when the prices are strategic substitutes, the average price is adjusted to a new equilibrium price instantaneously after each shock. This finding is consistent with the previous experimental finding by Fehr and Tyran (2008) as well as theoretical

[11]In the treatment with the menu cost where the first shock in $t = 16$ is negative, we see that the average price jumps up in the periods around $t = 25$, where no shock occurs. In that treatment, some subjects seem to have attempted to manipulate the outcome by raising their prices, probably in order to gain higher profits. However, the attempt failed, leading to lower profits for those who joined the move.

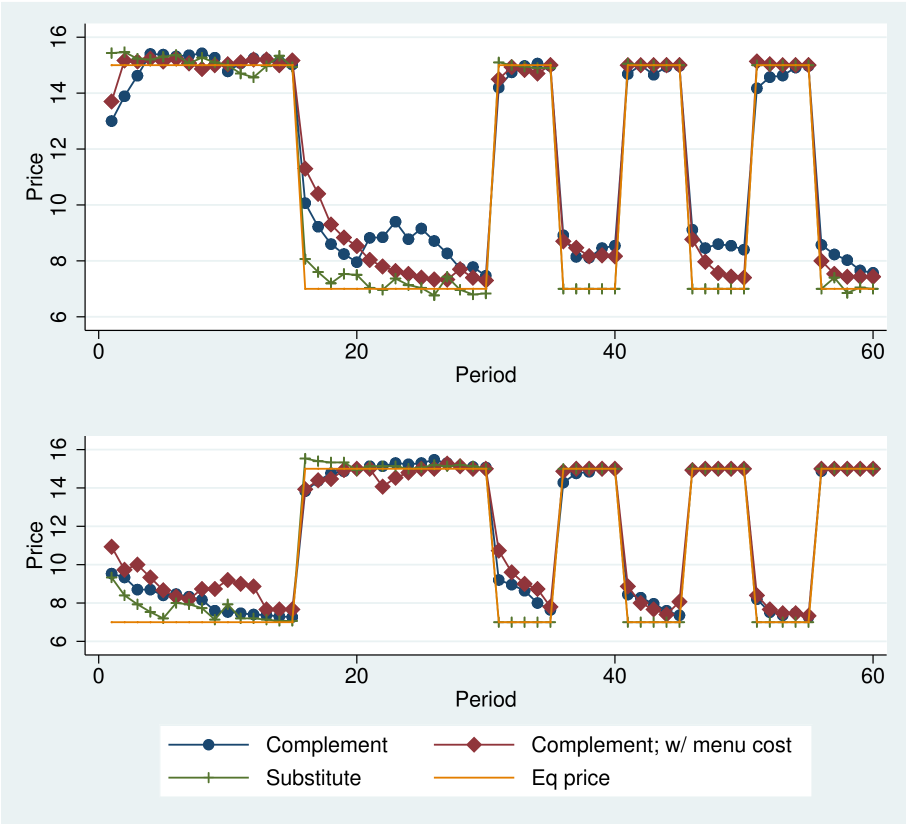


Figure 1: Evolution of Average Prices

Notes: *Complements* and *Substitutes* represent the treatments under strategic complementarity ($\zeta = 0.5$) and under strategic substitutability ($\zeta = -0.5$), respectively, both without menu costs. *Complements w/menu cost* represents the treatment where subjects incur a menu cost when they revise their prices.

Table 3: Average Deviations from Post-shock Equilibrium Prices

	Complements		Substitutes	
Periods	Negative cost push	Postive cost push	Negative cost push	Positive cost push
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 equilibrium price in period t, respectively. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

predictions by, for example, Haltiwanger and Waldman (1989) and Woodford (2003a).

Let us also note that, under strategic complementarity, the direction of cost shocks also affects the duration of deviation from the equilibrium. We can see in Figure 1 that negative cost push shocks lead to a longer time of adjustment. Indeed, Table 3 shows that even under strategic complementarity, the first positive cost push shock leads to a statistically significant deviation from the equilibrium only for two periods. This contrast suggests that strategic complementarity is only a necessary component to generate price stickiness, but not sufficient.

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

3.2 Individual Decisions

In order to understand why we observe price stickiness under the combination of i) strategic complementarity and ii) negative cost push 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

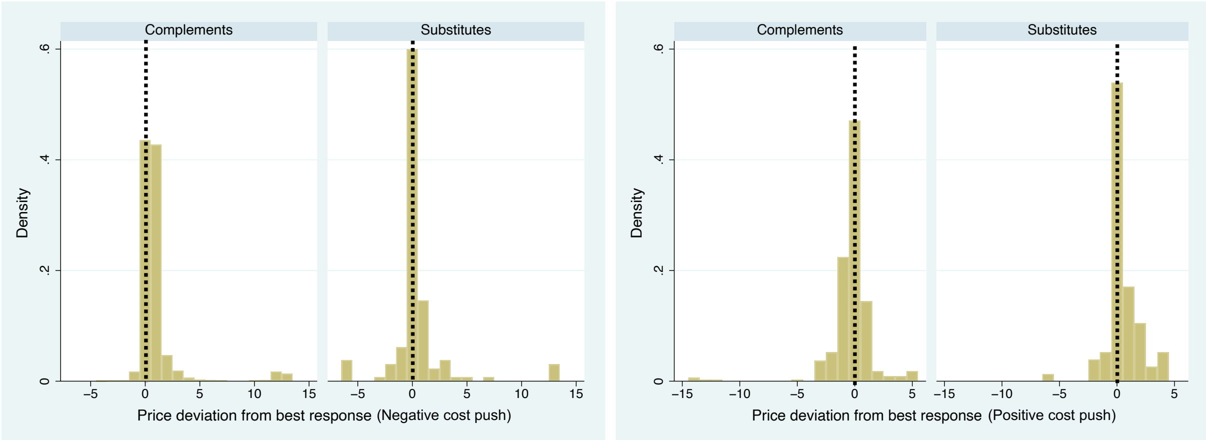


Figure 2: Histograms of Deviations from Best-Response Prices Based on Beliefs
Notes: The best-response price is defined as the price that maximizes subject i's profit when the average price set by the other subjects in her group equals i's stated belief. The density is calculated from the sample, where periods$\geq$ 16 and either subject i's own price or i's group average price does *not* equal the respective equilibrium price. *Complements* and *Substitutes* represent the treatments under strategic complementarity ($\zeta = 0.5$) and strategic substitutability ($\zeta = -0.5$), respectively, both without menu costs.

slow price adjustment increases the individual profits, with respect to the hypothetical scenario where they choose the new equilibrium price immediately after each shock, given the *observed* behavior of the other subjects.

3.2.1 Response to Stated Beliefs

In Figure 2, we see that the subjects largely best respond to their own stated beliefs in price setting, even out of equilibrium. Figure 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 without menu costs, such that subject i's own price or i's group average price differs from the equilibrium price (i.e. any observations that match the equilibrium prediction are excluded) for $t \geq 16$, i.e. after the first shock. Figure 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).

Meanwhile, the left panel of Figure 2 also indicates that the deviation from the best response is systematically biased after negative cost push shocks under strategic complementarity. For such shocks, the mode is zero (i.e. subjects best responded to the stated

Figure 3: Histograms of Changes in Prices and Beliefs

Notes: The fraction is calculated from the sample, where equilibrium changes, that is, at period= 16, 31, 36, 41, 46, 51, or 56. *Complements* and *Substitutes* represent the treatments of strategic complementarity ($\zeta = 0.5$) and strategic substitute ($\zeta = -0.5$), respectively, both without menu costs.

belief) but the second-highest density is at one, which implies that a number of subjects' prices were one unit above their best response.

Figure 3 presents how much subjects change their prices and beliefs immediately after the shocks in periods $t = 16, 31, 36, 41, 46, 51$, and 56. 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 Figure 3 that immediate individual price adjustments are smaller after negative cost push shocks than positive cost push shocks. For example, the mode of price adjustment immediately after negative cost push shocks is -7, one unit higher than the equilibrium, while the mode after cost push shocks is 8, which is consistent with the equilibrium. Moreover, the mean and variance of price adjustment for negative cost push shocks are -6.577 and 2.349, respectively, and those for positive cost push shocks are 7.108 and 2.021, 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 push shocks.

We observe a similar pattern for adjustments in beliefs. The mean and variance of belief adjustment after negative cost push shocks is are -6.186 and 2.434, respectively, and those after positive cost push shocks are 6.800 and 1.965, respectively. The difference in the means of belief adjustment in absolutely terms is again statistically significant at the 1% level, so that that the belief adjustment is smaller after negative cost push shocks than positive cost push 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 Figure 2, there is a systematic upward bias relative to the stated beliefs after negative cost push shocks. The levels of belief and price adjustments are dispersed after both positive and negative cost push shocks, and the adjustments are smaller after negative cost push shocks. Note that immediately after positive cost push 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 push 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.

3.3 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 push 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 push shocks for the treatment with strategic complementarity and no menu cost. We use the data only for $t \geq 16$ where either subject's own price or subject's group average price does not coincide with the equilibrium price. We

Table 4: Regression of Deviation from Best Response after Negative Cost Push 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 equilibrium 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 equilibrium 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 ($\zeta = 0.5$) and no menu cost. 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.

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 Figure 2, the negative coefficient indicates that after negative cost push shocks, uncertainty (low confidence) about the other subjects' average price leads to a higher price than the best response with respect to their beliefs. We do not obtain statistically significant association between uncertainty and pricing for positive cost push 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 equilibrium 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.

Table 5: Regression of Change in Beliefs

	Negative cost push			Positive cost push		
	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 ($\zeta = 0.5$) and no menu cost. Figures in parentheses indicate the standard errors. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

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 push shocks. We hypothesize that this is related to the payoff structure. Consider the payoff table (in Table 2) under strategic complementarity where the equilibrium price is 7, so that a switch to the payoff table represents a negative cost push 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 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.[12]

Due to the asymmetry in the payoff table, after a negative cost push shock, if the average price of the other subjects is the previous equilibrium 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 equilibrium faster than others others can be "penalized" heavily. This may have led subjects to adjust their beliefs and prices slowly.[13] As we have seen earlier, pricing is biased upwards with respect to the

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

[13] A similar asymmetry is present in the payoff tables used in the nominal treatments of Fehr and Tyran (2001, 2008), which suggests that price stickiness is attributed not just money illusion but also payoff asymmetry.

stated belief, and we may also attribute this to the asymmetry in the payoff table. For example, 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.[14] For even higher average prices of the others, the disproportionately large losses when a subject's own price is low may look salient to subjects on the profit table, and this may have further added 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 higher equilibrium price of 15 features the same type of asymmetry in that setting a lower price relative to the best response can hurt more than setting a higher price. However, since the shocks induce an upward shift in the equilibrium 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 equilibrium price may not have looked as risky as otherwise, even if a subject is uncertain about the average price of the others. This may explain why the aggregate price adjustments are much faster.

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.

So far we argued that both strategic uncertainty and asymmetric payoff structure, in addition to strategic complementarity, are crucial components to generate price stickiness. To examine our argument more formally, in what follows we present two types of

[14] 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.

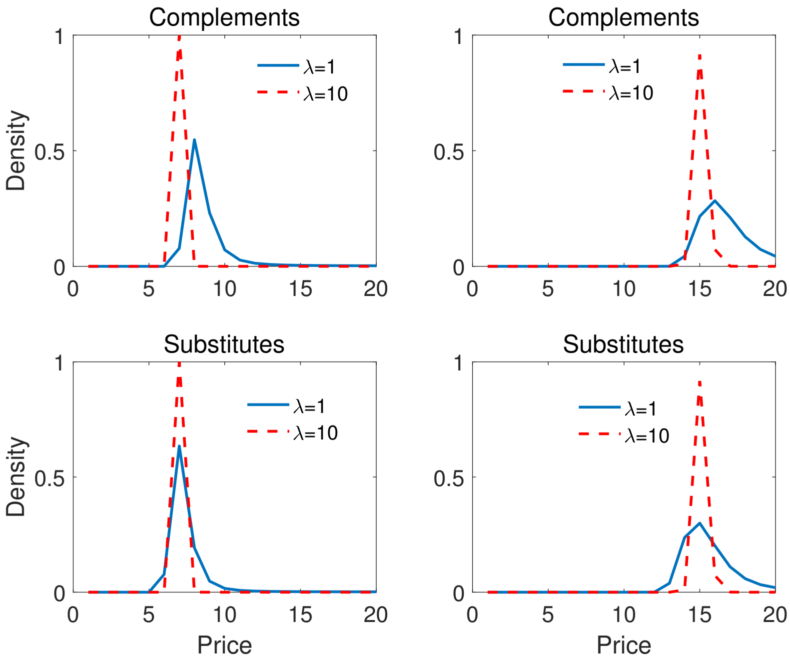


Figure 4: Distributions of Prices in Logit Quantal Response Equilibrium

Notes: λ represents the bounded rationality parameter, such that $\lambda \to \infty$ corresponds to perfectly rational players. The derivation of the logit quantal response equilibrium is given in Appendix A.

quantification, namely quantal response equilibrium, and individual pricing based on the belief that the others do not necessarily adjust their prices in every period.

3.3.3 Quantal Response Equilibrium

In order to quantify the characteristics of the payoff tables and their interactions with strategic uncertainty, Figure 4 presents the distributions of prices in the logit quantal response equilibrium (QRE). QRE is an extension of the standard notion of equilibrium, in which subjects make errors. The purpose of this analysis is not to explain our findings in terms of the QRE, but to illustrate what prices are likely to lead to higher or lower profits when all players are susceptible to making stochastic errors and therefore face strategic uncertainty. See Appendix A for the detail. We can see immediately that under strategic substitutability, the mode of the price distribution coincides with that of the equilibrium price for both the high and low equilibrium prices, which suggests that adjustment to an equilibrium price should be fast even with bounded rationality since setting the equilibrium price is least likely to lead to losses. In contrast, the distributions of prices under strategic complementarity when λ is lower (i.e. the players are more likely to make mistakes) have modes above the respective equilibrium prices, and the overall distributions are shifted to the right. This implies that, in line with our earlier discussion, given uncertainty about the prices of the others, charging a higher price than

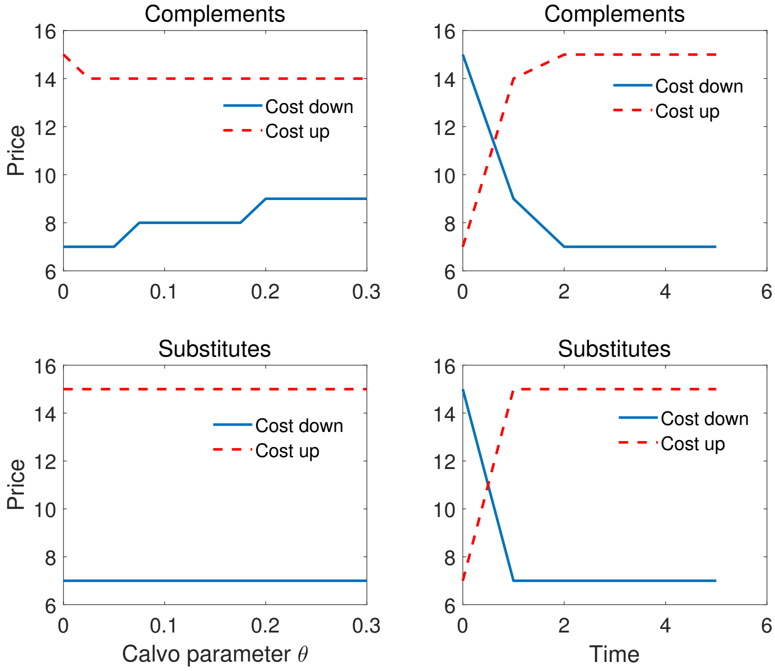


Figure 5: Prices immediately after a shock (left) and prices over time given $\theta = 0.25$ (right)

Notes: θ represents the subjective probability that each of the other agents does not reset their prices in the current period. The derivation of the subjective profit maximizing price given the (incorrect) belief is given in Appendix B.

the equilibrium price is likely to lead to higher profits.

However, unlike the distributions of prices in Figure 4, we hardly observe prices above the equilibrium price after the positive cost push shock in any treatments. One natural explanation is that a pre-shock equilibrium price serves as an anchor. This prevents subjects from overshooting the equilibrium price after positive cost push shocks.

3.3.4 Subjective Uncertainty on Calvo-Type Price Stickiness

While QRE helps explain partial price adjustments after shocks in the presence of strategic complementarity and asymmetric payoff structure, this does not necessarily explain price dynamics, that is, gradual convergence to an equilibrium price. In order to incorporate strategic uncertainty regarding individual decision making into our framework, we make the following assumption on each firm's belief and best response: every firm believes that each of the other firms is unable to reset the price in the previous period with probability θ (otherwise, they can set a profit maximizing price just as the firm itself does), but every firm does actually reset its price with probability 1 to maximize the expected profit given the belief. This is in the spirit of a Calvo-type time-dependent sticky price model, but differs in that the belief is incorrect, since all firms do choose their prices in every period based on the incorrect belief. While this approach is not an equilibrium analysis, it allows us to study the dynamics of price adjustments systematically given the belief that other firms may not adjust their prices. See Appendix B for the detail.[15]

Figure 5 depicts individual price responses to shocks, assuming that the price before the shock is the pre-shock equilibrium price. The left-hand panels represent the price in the period immediately after a shock (which corresponds to period 1 in the right-hand panels). We can see that under strategic substitutability and $\theta \leq 0.3$, the individual price is adjusted to the new equilibrium price immediately, while under strategic complementarity the price adjustments in the period of the shock are smaller as price stickiness θ becomes larger. In other words, the uncertainty about the other firms' price adjustment has a considerable effect on pricing only under strategic complementarity. We also see under strategic complementarity that price adjustment is smaller after the negative cost push shock than after the positive cost push shocks. In the right-hand panels, assuming $\theta = 0.25$, we observe gradual price convergence to the equilibrium only when prices are strategic complements, and moreover the speed of convergence is slower after the negative cost push shock than after the positive cost push shocks, as consistent with our earlier observation of the experimental data and discussion on the payoff structure.

3.4 Realized Payoffs

Table 6: Changes in Profits when Subjects Choose Different Prices after the First Shock

	Complements		Substitutes	
	Negative cost push	Positive cost push	Negative cost push	Positive cost push
If price set was				
Optimal price	2.47***	1.48***	1.74***	0.38**
Equilibrium	−5.53***	1.41***	1.74***	0.32
Old equilibrium	−3.28***	−13.63***	−5.49***	−15.09***
Optimal adaptive	−1.54***	−13.36***	−4.63***	−2.36***

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 equilibrium price in period t, while *Old equilibrium* indicates the equilibrium price before costs change. *Optimal adaptive* 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. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

Let us conclude our analysis of the main treatments with Table 6, 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

[15]Wang and Werning (2022) and Ueda (2023) study oligopolistic competition under strategic complementarity where the firms reset their prices under Calvo-type price stickiness, and examine the implications of price stickiness on monetary policy. In their models, the firms hold correct beliefs in equilibrium.

and the hypothetical profits, namely the mean of $\Pi^*_{it} - \Pi_{it}$ across i's, where Π_{it} and Π^*_{it} represent the actual profit of subject i in period $t = 16$ and the hypothetical profit of subject i in period $t = 16$, respectively. The four strategies of each subject considered in Table 6 are as follows: (i) the price that maximizes Π^*_{it} given the actual average price of the other subjects we observe ex post; (ii) the equilibrium price in period t; (iii) the old equilibrium price, that is, the equilibrium price before a shock; and (iv) the profit that maximizes Π^*_{it} given the adaptive belief such that the average price of the other subjects is the same as that in period $t = 15$. 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 push 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 equilibrium price indicates that subjects would have earned much smaller profits by doing so. In this regard, subjects' small adjustment to the equilibrium price is individually beneficial for them. Moreover, subjects would also have earned lower profits if (iii) they had not revised their pries at all. Finally, 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.[16] 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 push shock, choosing the equilibrium 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 6, 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 equilibrium price was focal at least among sophisticated subjects.

3.5 Price Stickiness and Payoff (A)symmetry

We have seen so far that the marked price stickiness is observed only after negative cost push shocks under strategic complementarity. We have argued that this is because of strategic uncertainty and the specific payoff structure. In order to examine whether this

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

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

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

Table 7: Symmetric Profit Tables

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.

specific feature of the payoff structure accounts for the observed stickiness along with strategic complementarity, 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 equilibrium price. Relevant parts of the profit tables are shown in Table 7. 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. 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) equilibrium price faster than others does not lead to a large loss either.[17] We kept the other features of the profit tables as similar as possible to those in the main treatments.

Figure 6 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

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

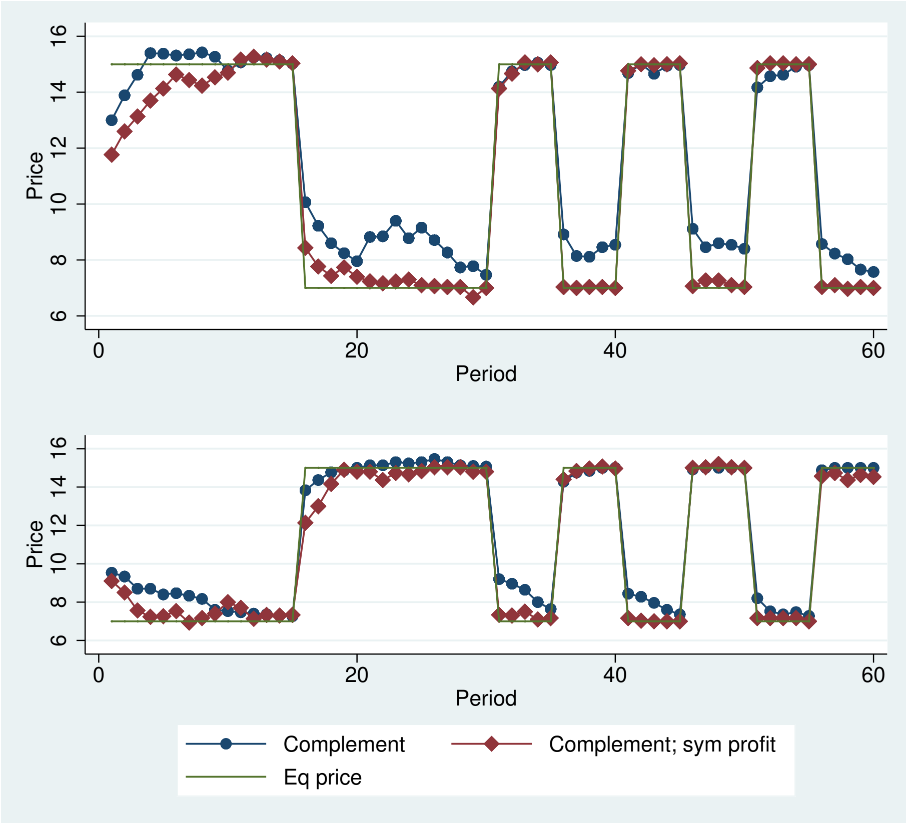


Figure 6: Evolution of Average Prices (Asymmetric vs Symmetric Profits)

payoffs. After the first negative cost push shock, the deviation from the equilibrium 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 push shock, the deviation from the equilibrium price is the deviation from the equilibrium price is negative and significantly different from zero at the ten percent level also for $t = 16, 17$ and 18. Therefore, unlike the treatments whose payoff tables are drawn from the price setting game, the level of deviation from the respective equilibrium price is similar between both types of shocks.

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. This supports our argument that the price stickiness we observe is caused by the combination of three factors, namely i) strategic complementarity; ii) strategic uncertainty; and iii) asymmetric payoff structure that heavily penalizes faster adjustment to the equilibrium than others.

4 Concluding Remarks

This paper presents an elementary but novel approach 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 push 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. Specifically, 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 equilibrium 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 push 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 equilibrium 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: Logit Quantal Response Equilibrium

The logit quantal response equilibrium presented in Figure 4 is derived as follows. Denote by P_i^k a specific price firm i posts where $P_i^k = k$ and $k \in \{1, 2, ..., 20\}$. Let f_i^k be the probability that firm i posts P_i^k, and let f_i be the probability distribution of firm i's prices. In the logit quantal response equilibrium, we have

$$f_i^k = \frac{\exp(\lambda EU_i^k(f_{-i}))}{\Sigma_l \exp(\lambda EU_i^l(f_{-i}))},$$

where $EU_i^k(p_{-i})$ is the expected profit of firm i when choosing P_i^k, given that the distribution of prices of the other four firms is identical to f_i and denoted by f_{-i}. We have $f_i^k = 1/20$ (uniformly distributed price) as $\lambda \to 0$, and f_i converges to the equilibrium price (7 or 15 depending on the payoff table) as $\lambda \to \infty$. Given the payoff table, it is sufficient to treat f_{-i} as the distribution of the average prices of the other firms rounded to the nearest integers.[18]

Appendix B: Subjective Uncertainty on Calvo-type Price Stickiness

The prices in Figure 5 are computed as follows. We assume that a shock occurs in period $t = 1$ and all firms' prices in $t = 0$ (i.e. before the shock) are at the pre-shock equilibrium price. In each period $t \geq 1$, the price that maximizes a firm's subjective expected profit, $P_{i,t}^*$, is given by

$$P_{i,t}^* = \underset{P_{i,t} \in \{1,2,...,20\}}{\arg\max} \; \mathbb{E}_i \left[\Pi(P_{i,t}, \bar{P}_{-i,t}) | P_{t-1}, \theta \right],$$

where $\mathbb{E}_i[\cdot]$ represents firm i's subjective belief, $\bar{P}_{-i,t} = \sum_{j \neq i} P_{j,t}/4$ is the average price of the other firms $j \neq i$ in period t, and $P_{j,t}$ evolves as

$$P_{j,t} = \begin{cases} \bar{P}_{-i,t-1} & \text{with prob.} \theta \\ P_{j,t}^* & \text{with prob.} 1 - \theta. \end{cases}$$

Figure 5 plots $P_{i,t}^*$ for each case. As noted in the main text, this is not an equilibrium analysis since all firms actually reset their prices every period and thus the belief on $P_{-i,t}$ is incorrect.[19]

[18] The MATLAB code for Figure 4 is available upon request.
[19] The MATLAB code for Figure 5 is available upon request.

Appendix C: 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.

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) $\div$ 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 (Figure 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.

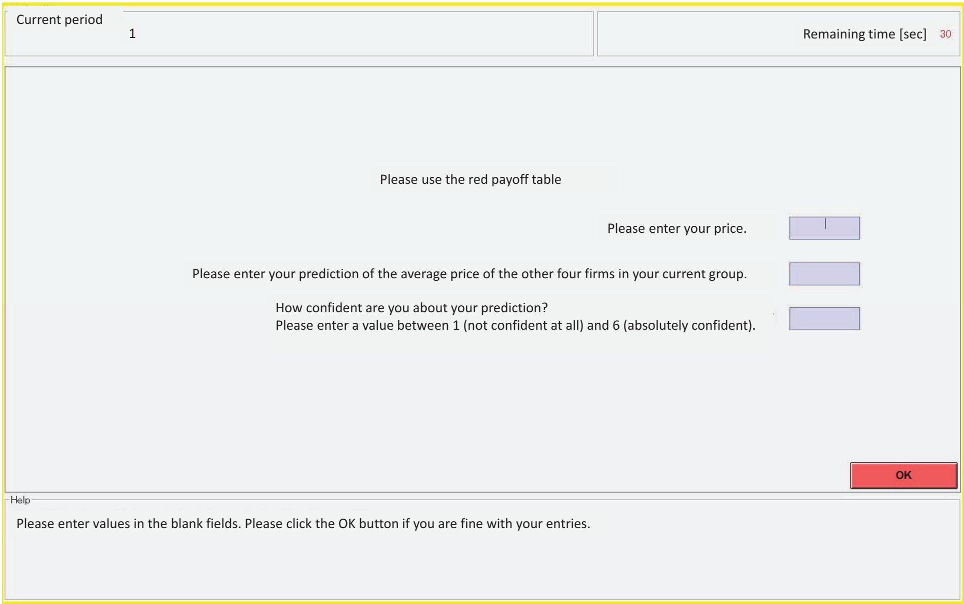
For example, let us suppose you predict that the average price will be 4. In this case, if you select a price of 2, then the predicted value of the profit earned by your company will be -1.00.

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 Figure 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.

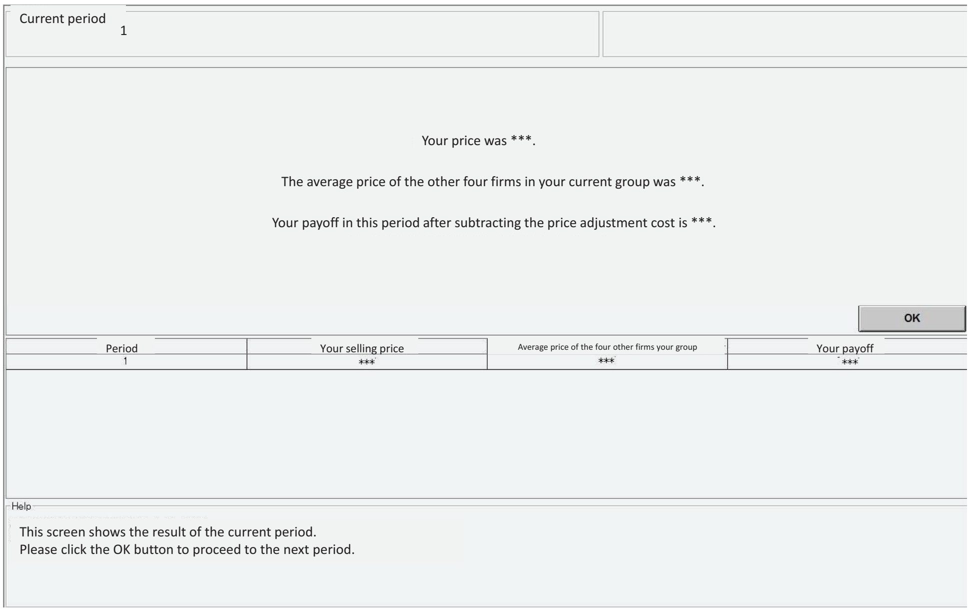
5: I am confident that my prediction is correct.

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 (Figure 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[20]

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, $P^* = 15$

[20] P^* below denotes the equilibrium price for each case.

References

[1] Adam, Klaus. 2007. “Experimental Evidence on the Persistence of Output and Inflation.” *Economic Journal*, 117, 603–636.

[2] Alvarez, Luis, and Ignacio Hernando. 2005. “The Price Setting Behaviour of Spanish Firms: Evidence from Survey Data.” ECB Working Paper Series, No. 522.

[3] Amano, Robert, Oleksiy Kryvtsov, and Luba Petersen. 2014. “Recent Developments in Experimental Macroeconomics.” *Bank of Canada Review*, Autumn 2014, 1–11.

[4] Andreoni, James, Nikos Nikiforakis, and Simon Siegenthaler. 2021. “Predicting Social Tipping and Norm Change in Controlled Experiments.” *Proceedings of the National Academy of Sciences*, 118, e2014893118.

[5] Angeletos, George-Marios, Zhen Huo and Karthik A. Sastry. 2020. “Imperfect Macroeconomic Expectations: Evidence and Theory.” *NBER Macroeconomics Annual*, 35, 1-86.

[6] Assenza, Tiziana, Peter Heemeijer, Cars Hommes, and Domenico Massaro, 2013. “Individual Expectations and Aggregate Macro Behavior.” Tinbergen Institute Discussion Paper, No. 13-016/II.

[7] Baeriswyl, Romain, Kene Boun My, and Camille Cornand, 2020. “Double Overreaction in Beauty Contests with Information Acquisition: Theory and Experiment.”, 118, *Journal of Monetary Economics*, 432-445.

[8] Bils, Mark and Peter J. Klenow. 2004. “Some Evidence on the Importance of Sticky Prices.” *Journal of Political Economy*, 112, 947–985.

[9] Blanchard, Oliver, and Nobuhiro Kiyotaki. 1987. “Monopolistic Competition and the Effects of Aggregate Demand.” *American Economic Review*, 77, 647–666.

[10] Charness, Gary, Uri Gneezy, and Vlastimil Rasocha. 2021. “Experimental Methods: Eliciting Beliefs.” *Journal of Economic Behavior and Organization*, 189, 234—256.

[11] Cornand, Camille, and Frank Heinemann. 2014a. “Experiments on Monetary Policy and Central Banking.” in: John Duffy (ed.), *Experiments in Macroeconomics*, Research in Experimental Economics, Vol. 17, Bingley, UK: Emerald, 167–227.

[12] Cornand, Camille, and Frank Heinemann. 2014b. “Measuring Agents’ Overreaction to Public Information in Games with Strategic Complementarities.” *Experimental Economics*, 17, 61–77.

[13] Davis, Douglas, and Oleg Korenok. 2011. “Nominal Shocks in Monopolistically Competitive Markets: An Experiment.” *Journal of Monetary Economics*, 58, 578–589.

[14] Dixit, Avinash K. and Joseph E. Stiglitz. 1977. “Monopolistic Competition and Optimum Product Diversity.” *American Economic Review*, 67, 297–308.

[15] Duffy, John. 2016 “Macroeconomics: A Survey of Laboratory Research.” in: J. H. Kagel and A.E. Roth (Eds.), *Handbook of Experimental Economics Volume 2*, Princeton: Princeton University Press, 1–90.

[16] Duffy, John, and Jonathan Lafky. 2021. “Social Conformity under Evolving Private Preferences.” *Games and Economic Behavior*, 128, 104—124.

[17] Farhi, Emmanuel and Iván Werning. 2019. “Monetary Policy, Bounded Rationality, and Incomplete Markets.” *American Economic Review*, 109, 3887–3928.

[18] Fehr, Ernst, and Jean-Robert Tyran. 2001. “Does Money Illusion Matter?” *American Economic Review*, 91, 1239–62.

[19] Fehr, Ernst, and Jean-Robert Tyran. 2007. “Money Illusion and Coordination Failure.” *Games and Economic Behavior*, 58, 246—268.

[20] Fehr, Ernst, and Jean-Robert Tyran. 2008. “Limited Rationality and Strategic Interaction: The Impact of the Strategic Environment on Nominal Inertia.” *Econometrica*, 76, 353–94.

[21] Fehr, Ernst, and Jean-Robert Tyran. 2014. “Does Money Illusion Matter?: Reply.” *American Economic Review*, 104, 1063–1071.

[22] Fischbacher, Urs. 2007. “Z-tree: Zurich Toolbox for Ready-Made Economic Experiments.” *Experimental Economics*, 10 (2), 171–178.

[23] Gabaix, Xavier. 2020. “A Behavioral New Keynesian Model.” *American Economic Review*, 110, 2271–2327.

[24] Garcıa-Schmidt, Mariana and Michael Woodford. 2019. “Are Low Interest Rates Deflationary? A Paradox of Perfect-Foresight Analysis.” *American Economic Review*, 109, 86–120.

[25] Giamattei, Marcus, and Johann G. Lambsdorff. 2015. “Balancing the Current Account: Experimental Evidence on Underconsumption.” *Experimental Economics*, 18, 670–696.

[26] Haltiwanger, J. and M. Waldman. 1989. "Limited Rationality and Strategic Complements: The Implications for Macroeconomics," *Quarterly Journal of Economics*, 104, 463–484.

[27] Kimball, Miles. 1995. "The Quantitative Analytics of the Basic Neomonetarist Model." *Journal of Money, Credit and Banking*, 27, 1241–1277.

[28] Kryvtsov, Oleksiy and Luba Petersen. 2015. "Expectations and Monetary Policy: Experimental Evidence." working paper, Bank of Canada.

[29] Lambsdorff, Johann G, Manuel Schubert, and Marcus Giamattei. 2013. "On the Role of Heuristics—Experimental Evidence on Inflation Dynamics." *Journal of Economic Dynamics and Control*, 37, 1213–1229.

[30] Luhan, Wolfgang J., and Johann Scharler. 2014. "Inflation Illusion and the Taylor Principle: An Experimental Study." *Journal of Economic Dynamics and Control*, 45, 94–110.

[31] Magnani, Jacopo, Aspen Gorry, and Ryan Oprea. 2016. "Time and State Dependence in an Ss Decision Experiment: Dataset." *American Economic Journal: Macroeconomics*. 8, 285–310.

[32] Nimark, Kristoffer. 2008. "Dynamic Pricing and Imperfect Common Knowledge." *Journal of Monetary Economics*, 55, 365–382.

[33] Noussair, Charles N., Damjan Pfajfar, and Janos Zsiros. 2015. "Pricing Decisions in an Experimental Dynamic Stochastic General Equilibrium Economy." *Journal of Economic Behavior and Organization*, 109, 188–202.

[34] Petersen, Luba, and Abel Winn. 2014. "Does Money Illusion Matter?: Comment." *American Economic Review*, 104, 1047–1062.

[35] Pfajfar, Damjan, and Blaz Zakelj. 2014. "Experimental Evidence on Inflation Expectation Formation." *Journal of Economic Dynamics and Control*, 44, 147–168.

[36] Pfajfar, Damjan, and Blaz Zakelj. 2016. "Inflation Expectations and Monetary Policy Design: Evidence from the Laboratory." *Macroeconomic Dynamics*, 22, 1035—1075.

[37] Schlag, Karl, James Tremewan, and Joel van der Weele. 2015. "A Penny for Your Thoughts: A Survey of Methods for Eliciting Beliefs." *Experimental Economics*, 18, 457—490.

[38] Schotter, Andrew, and Isabel Trevino. 2014. "Belief Elicitation in the Laboratory." *Annual Review of Economics*, 6, 103—128.

[39] Smerdon, David, Theo Offerman, and Uri Gneezy. 2020. "'Everybody's Doing It': On the Persistence of Bad Social Norms." *Experimental Economics,* 23, 392-420.

[40] Ueda, Kozo. 2023. "Duopolistic Competition and Monetary Policy." *Journal of Monetary Economics*, 135, 70–85.

[41] Wang, Olivier, and Iván Werning. 2022. "Dynamic Oligopoly and Price Stickiness." *American Economic Review*, 112, 2815–49.

[42] Wilson, Bart J. 1998. "Menu Costs and Nominal Price Friction: An Experimental Examination." *Journal of Economic Behavior and Organization*, 35, 371–388.

[43] Winn, Abel. 2015 "The Effects of Focal Points and the Strategic Environment on Nominal Price Inertia." Working Paper.

[44] Woodford, Michael. 2003a. *Interest and Prices: Foundations of a Theory of Monetary Policy*. Princeton, NJ: Princeton University Press.

[45] Woodford, Michael. 2003b. "Imperfect Common Knowledge and the Effects of Monetary Policy." *Knowledge, Information, and Expectations in Modern Macroeconomics: In Honor of Edmund S. Phelps*. Princeton, NJ: Princeton University Press.