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Duopolistic competition and monetary policy☆

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ABSTRACT

To consider the strategic pricing of duopolistic firms and its implications for monetary policy, this study constructs a tractable duopoly model with price stickiness. Dynamic strategic complementarity, in which an increase in a firm's price increases the optimal price set by the rival firm in the following periods, increases steady-state price and the real effect of monetary policy. However, when temporary sales arise as a mixed strategy, the real effect of monetary policy decreases considerably.

1. Introduction

Models based on monopolistic competition provide a simple framework to analyze firms' price-setting behavior, which enables us to study the effects of monetary policy in tractable macroeconomic models (see Blanchard and Kiyotaki, 1987; Dixit and Stiglitz, 1977). However, aside from certain exceptions, these models focus on cases in which the number of firms is infinite and do not incorporate the strategic behaviors of oligopolistic firms. Firms in the model do not need to consider how their price influences their rival firms' prices and how a rival firm's price influences their optimal price. However, in reality, firms compete with a finite number of rival firms, and they closely monitor the pricing of only a limited number of rival firms (particularly market leaders). These observations motivate us to consider the role of the strategic pricing of oligopolistic firms in macroeconomic models.

This study aims to investigate how implications for monetary policy change when we incorporate the strategic pricing behaviors of oligopolistic firms into the sticky-price model. The first objective of this study is to demonstrate analytically and numerically how demand influences dynamic (intertemporal) strategic complementarity and, in turn, the effect of monetary policy. We construct a macroeconomic model with Calvo-type price stickiness by incorporating oligopolistic competition. Demand is described by an arbitrary invertible demand system, which encompasses the constant elasticity of substitution (CES) preferences and Hotelling's (1929) address model (see Pettengill, 1979, Dixit and Stiglitz, 1979, Anderson et al., 1992 for the similarities and differences between the CES and Hotelling models).

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The second objective of this study is to consider how the implications of temporary sales (price discounts) for the effect of monetary policy change when we incorporate the strategic pricing behaviors of oligopolistic firms. It is widely known that temporary sales are held frequently and that price stickiness decreases considerably once we include sales in the measurement of price stickiness (see, e.g., Klenow and Kryvtsov, 2008 for the United States and Sudo et al., 2014 for Japan). This implies that the use of temporary sales is an important source of price flexibility for firms that face costs of regular price adjustments, which might decrease the real effect of monetary policy. Further, temporary sales may be determined by strategic motives and are therefore potentially important in understanding the response of prices in oligopolistic markets. We consider a mixed strategy equilibrium, where the higher and lower prices constitute the regular and sale prices, respectively.

Our main results are as follows. First, we show analytically and numerically how demand influences dynamic (intertemporal) strategic complementarity.[1] We solve the Markov equilibrium in our dynamic game using log-linearization around the steady state. The pricing strategy of every firm is formulated based on its rival's past price, its own past price, and an aggregate shock in the current period. Particularly, in our model, a firm's own price positively influences the price set by the rival firm in the following periods (dynamic strategic complementarity). This effect increases as cross elasticity increases, the absolute value of own superelasticity (the elasticity of elasticity) decreases, or cross superelasticity increases. An increase in cross elasticity suggests that demand increases more as the rival increases its price, which amplifies dynamic strategic complementarity. Own and cross superelasticities are the second derivative with respect to a firm's own price and the cross derivative with respect to a firm's own and its rival's prices, respectively, which tend to be negative and positive. Quasi kinked demand (Kimball, 1995) is an example of an increase in the absolute value of own superelasticity, which is often considered to increase dynamic strategic complementarity. However, we present the opposite result: It decreases dynamic strategic complementarity. By contrast, an increase in cross superelasticity increases dynamic strategic complementarity: When demand becomes more (less) elastic as the rival lowers (raises) its price, dynamic strategic complementarity increases, which slows the process of price adjustments in response to an aggregate shock.

Second, we find that an increase in dynamic strategic complementarity is associated with an increase in price markup under sticky prices and an increase in the real effect of monetary policy. Because of dynamic strategic complementarity, the expectation that the rival firm may not revise its price on a given day under price stickiness discourages a firm from revising its price aggressively on that given day, which decreases the nominal effect of monetary policy (i.e., price response) and increases the real effect of monetary policy (i.e., output response). The steady-state price markup increases from 12.5% to 13.8%, and the real effect of monetary policy increases by approximately 50%.

Finally, we find that the real effect of monetary policy decreases considerably under duopoly if there is a mixed strategy equilibrium (i.e., if temporary sales exist). We show that a mixed strategy equilibrium can arise when own demand elasticity depends on the rival's price, unlike in the case of CES preferences. Particularly, when we incorporate the Hotelling model with consumer heterogeneity in terms of transport costs, a mixed strategy equilibrium arises such that temporary sales exemplify strategic complementarity for the interaction between setting the higher price and the lower price, whereas dynamic strategic complementarity decreases for the interaction between setting the higher prices by two firms. We find that, in response to a monetary easing shock, output under the mixed strategy equilibrium in the Hotelling model with transport-cost heterogeneity increases by less than one-tenth than that under the pure strategy equilibrium in the Hotelling model without transport-cost heterogeneity.

The three studies most similar to ours are those by Faia (2012), Mongey (2017), and Wang and Werning (2022), who investigate monetary policy under oligopolistic competition.[2] Particularly, Wang and Werning's (2022) work is the closest to this study. They consider strategic pricing behavior under nominal rigidity and find that higher market concentration amplifies the real effect of monetary policy. They demonstrate an empirically useful closed-form relation for the degree of dynamic strategic complementarity using observable markup. The main contribution of this study relative to that of Wang and Werning (2022) is that first, while both studies derive a closed-form relation between the steady-state price (markup) and the degree of dynamic strategic complementarity, unlike their study, our research obtains a closed-form solution for the degree of dynamic strategic complementarity. Using a general model, we express it with structural parameters associated with the demand system. In this way, we demonstrate how demand parameters consisting of own elasticity, cross elasticity, and three kinds of superelasticity influence the degree of dynamic strategic complementarity. Particularly, we show that an increase in superelasticity does not necessarily increase dynamic strategic complementarity. To increase dynamic strategic

[1] See Jun and Vives (2004) and Mongey (2017) for the terminology of *static* and *dynamic* (intertemporal) strategic effects. In short, nominal rigidity transforms static strategic effects into dynamic (intertemporal) ones. Mongey (2017) presents the following comparison: Without nominal rigidity, firms optimize their prices strategically and simultaneously (static complementarity), which causes all prices to change equally. With nominal rigidity, firms optimize their prices strategically and intertemporally because their price in the current period influences the prices of other firms in the following period (dynamic complementarity), which yields uneven price changes.

[2] Faia (2012), the first in this research area, considers optimal monetary policy when the number of firms is finite. However, Faia (2012) incorporates the effect of finiteness only partially: Each firm takes into account the effect of its price on the aggregate price but not the strategic effect of its price on the prices of other firms. Mongey (2017) introduces not only cross- but also within-sector elasticity of substitution to incorporate duopoly: Two firms exist in each sector, and they compete strategically by optimally changing prices in the context of a menu cost model of price adjustment with idiosyncratic shocks. Mongey (2017) shows that dynamic strategic complementarity decreases the responses of price adjustment and increases the real effect of monetary policy, which is consistent with the findings of our study. One may also refer to Nirei and Scheinkman (2020), who construct a comparable model, in which competition among a finite number of firms generates inflation volatility.

complementarity, an increase in cross, not own, superelasticity is necessary. Further, in our model, monetary policy shocks are stochastic, which enables us to analyze how firms' pricing responds to a monetary policy shock and how strategic pricing behavior changes the implications for the effects of monetary policy.

The second contribution of this study relative to that of Wang and Werning (2022) is that we investigate the role of temporary price sales in considering the effects of monetary policy. Empirically, it is well known that the degree of temporary sales varies across products (Nakamura and Steinsson, 2008), regions (Coibion et al., 2015), over business cycles (Kryvtsov and Vincent, 2021), and over time (Sudo et al., 2018). Theoretically, some studies argue that the implications of sales for the real effect of monetary policy are not important (Anderson et al., 2017; Guimaraes and Sheedy, 2011; Kehoe and Midrigan, 2015), while others deem them important (Sudo et al., 2018 and Kryvtsov and Vincent, 2021). Particularly, Guimaraes and Sheedy (2011) construct a New Keynesian model with heterogeneous elasticity of substitution and show that sales exist in equilibrium but the real effect of monetary policy is more or less unchanged. Our result is markedly different, showing that the real effect of monetary policy decreases considerably. The most important modeling difference is that the literature, including (Guimaraes and Sheedy, 2011), relies on models with monopolistic competition (no strategic motives), whereas our model is based on duopolistic competition and incorporates strategic pricing behaviors. We show that a mixed strategy equilibrium does not arise when own demand and its elasticity are independent of the rival's price, which suggests the importance of a departure from monopolistic competition based on CES preferences in explaining temporary sales as a mixed strategy equilibrium.

Among a number of contributions to the development of New Keynesian models, our study is related to works that stress the importance of strategic complementarity and real rigidity (see, e.g., Angeletos and La'O, 2009; Aoki et al., 2019; Ball and Romer, 1990; Christiano et al., 2005; Kimball, 1995; Levin et al., 2007; L'Huillier, 2020; Woodford, 2003). For example, Angeletos and La'O (2009) show that the combination of noisy information and strategic complementarity yields lasting effects of nominal shocks on inflation and real output. L'Huillier (2020) considers a strategic interaction between a monopolistic firm and uninformed consumers. Our study provides a new insight into the source of strategic complementarity from the perspective of an oligopoly.

This contribution builds on the extant literature studying the relations between strategic pricing and sticky prices. Fershtman and Kamien (1987) consider a duopolistic competition model, as we do, under the assumption that prices do not adjust instantaneously to the price indicated by a demand function. They study how the sticky price assumption changes Nash equilibrium strategies. Their work is different from this study in that their model is based on Cournot competition, and thus, firms are not price setters and instead optimize their output. Price changes are governed by an exogenous reduced-form equation. Accordingly, the author's research contribution does not directly identify implications for the macroeconomy. For further research on this topic, see Maskin and Tirole (1988), Slade (1999), Bhaskar (2002), Fehr and Tyran (2008), and Chen et al. (2017). These studies investigate whether price becomes sticky endogenously in a market where firms compete strategically.

The remainder of this paper is structured as follows. Section 2 presents the basic model and discusses its implications. Section 3 considers temporary sales as a mixed strategy equilibrium and investigates monetary policy effects. Section 4 concludes.

2. Duopolistic competition model with nominal stickiness

2.1. Setup

The head of a household maximizes the following preference: $U = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t [\log C_t - (L_t + \tau D_t)]$, where aggregate consumption C_t is given by $\log C = \int_0^1 \log c^j dj$, L_t represents labor supply, and shopping distance D_t is given by $D = \int_0^1 d^j dj$.[3] Here, c^j represents consumption for product line $j \in [0, 1]$, parameter $\beta \in (0, 1)$ is the subjective discount factor, and parameter $\tau \geq 0$ represents the transport cost incurred per unit of distance. Except for the (Hotelling, 1929) address model, one may assume $\tau = 0$.

The budget constraint is given by $M_t + B_t + P_t C_t \leq M_{t-1} + R_{t-1} B_{t-1} + W_t L_t + \Pi_t + T_t$, where M_t, B_t, P_t, R_t, W_t, Π_t, and T_t represent money supply, nominal bonds, aggregate price, nominal interest rate, nominal wages, dividends from firms, and lump-sum transfer, respectively. We assume that nominal spending must be equal to the money supply: $P_t C_t = M_t$. The first-order condition leads to $W_t = M_t = P_t C_t$.[4]

In each product line $j \in [0, 1]$, there exist n firms denoted by i. If there are two firms, we denote them as A or B ($i = A, B$). The quantity demanded for firm i's goods in period t, x_t^i, is described by an arbitrary invertible demand system $x_t^i = x^i(p_t^i, p_t^{-i}; M_t) = x^i(p_t^i/M_t, p_t^{-i}/M_t)$, where p_t^i and p_t^{-i} represent the prices set by firm i and its rivals, respectively. Demand invertibility is a mild technical requirement encompassing the demand system characterized by CES preferences, quasi kinked demand (Kimball, 1995), and the (Hotelling, 1929) address model. To produce one unit of a product, firms require one unit of labor, which costs W_t.

[3] We assume a log utility in consumption and linear disutility of labor supply as in Nakamura and Steinsson (2010) and Midrigan (2011). See also Hansen (1985) and Rogerson (1988).

[4] One may assume that the monetary authority targets a path for nominal output to ensure $P_t C_t = M_t$. Because $M_t = W_t$, money supply shocks are equivalent to changes in nominal marginal costs. See Nakamura and Steinsson (2010) and Midrigan (2011).

The goods market is cleared as $Y_t(=L_t)=C_t$. Money supply is exogenous and given by $\log(M_t/M_{t-1})=\varepsilon_t=\rho\varepsilon_{t-1}+\mu_t$, where μ_t is an i.i.d. shock to money supply growth. Money supply has a zero trend growth.

Given firm symmetry, demand is shared equally among the firms in each product line, which leads to $x^i\equiv M_t/(nP_t)=1/(np)$ in a steady state. We define own elasticity $\Psi^i\equiv\frac{\partial\log x^i(p^i/M,p^{-i}/M)}{\partial\log(p^i/M)}$, cross elasticity $\Psi^{-i}\equiv\frac{\partial\log x^i(p^i/M,p^{-i}/M)}{\partial\log(p^{-i}/M)}$, and three kinds of superelasticity (the elasticity of elasticity) $\Psi^{i,i}\equiv\frac{\partial\Psi^i}{\partial\log(p^i/M)}$, $\Psi^{-i,-i}\equiv\frac{\partial\Psi^{-i}}{\partial\log(p^{-i}/M)}$,and $\Psi^{i,-i}\equiv\frac{\partial\Psi^{-i}}{\partial\log(p^i/M)}=\frac{\partial\Psi^i}{\partial\log(p^{-i}/M)}$, which are important when considering monetary non-neutrality. Because two kinds of price, p^i and p^{-i}, exist, there are three kinds of superelasticity. We pay particular attention to $\Psi^{i,i}$ and $\Psi^{i,-i}$, which we call own superelasticity and cross superelasticity, respectively, while we do not provide a term for $\Psi^{-i,-i}$. In the following cases, we have negative Ψ^i and $\Psi^{i,i}$ and positive $\Psi^{i,-i}$. A negative own superelasticity suggests that own demand becomes more (less) elastic as own price increases (decreases), while a positive cross superelasticity suggests that own demand becomes more (less) elastic as the rival's price decreases (increases).

Constant returns to scale imply $(n-1)\Psi^{-i}=-(1+\Psi^i)$. We discuss the main results in the subsequent discussion and present the detailed derivations in Appendices A and B. We consider Ψ's in the following two special cases.

CES and Oligopolistic Competition

We assume $\tau=0$. For each product line j, consumption is aggregated following the CES form of aggregation: $c_t^j=\left\{\sum_{i=1}^n(1/n)^{1/\sigma}\left(x_t^i\right)^{\frac{\sigma-1}{\sigma}}\right\}^{\frac{\sigma}{\sigma-1}}$, where σ represents the elasticity of substitution. This yields the demand function given by $x_t^i=1/n\left(p_t^i/P_t\right)^{-\sigma}M_t/P_t$ and the aggregate price given by $P_t=\left\{\sum_{i=1}^n 1/n\left(p_t^i\right)^{1-\sigma}\right\}^{\frac{1}{1-\sigma}}$. Then, we obtain $\Psi^i=-\{(n-1)\sigma+1\}/n$, $\Psi^{-i}=(\sigma-1)/n, \Psi^{i,i}=\Psi^{-i,-i}=-(n-1)\{(1-\sigma)/n\}^2$, and $\Psi^{i,-i}=\{(1-\sigma)/n\}^2$. Although the demand function appears to show that x_t^i decreases with p_t^i with the own elasticity of σ, this is not precise. Since firms are oligopolistic, a firm's price p_t^i influences the aggregate price in the product line P_t. As the number of firms n decreases, this effect increases, and the absolute value of own elasticity ($|\Psi^i|$) decreases (increases) when $\sigma>1$ ($\sigma<1$). As $n\to\infty$, $|\Psi^i|$ converges to σ as in the monopolistic competition model. By contrast, cross elasticity Ψ^{-i} converges to zero as $n\to\infty$ when $\sigma>1$ ($\sigma<1$). Particularly, for $\sigma>1$ and finite n, Ψ^{-i} is positive, suggesting that an increase in the rival's prices increases own demand. Own and cross superelasticity ($\Psi^{i,i}$ and $\Psi^{i,-i}$) are different from zero unless $\sigma=1$ or $n\gg1$. Specifically, own superelasticity is negative when $\sigma>1$. Introducing quasi kinked demand further lowers own superelasticity.

Hotelling Address Model and Duopolistic Competition

A household comprises an infinite number of consumers who are uniformly located along the interval [0, 1].[5] A consumer located at $x\in[0,1]$ is at a distance x from firm A and $1-x$ from firm B. The consumer's net surplus is written as $u^i=\log c^i-\tau d^i=\log M-\log p^i-\tau d^i$, where d^i represents the distance the consumer travels to get to firm i. Although we call τ the transport cost throughout the paper, this parameter also represents consumers' choosiness, that is, how much they dislike buying from their less preferred firms. When τ is high, the consumers are loyal to their preferred firms. When τ is low, they care about the prices of the two firms, that is, they act as bargain hunters.

In this case, demand is given by $x_t^i=\left(\frac{1}{2}-\frac{\log(p_t^i/M_t)-\log(p_t^{-i}/M_t)}{2\tau}\right)\frac{M_t}{p_t^i}$ when $p_t^i\simeq p_t^{-i}$, which yields $\Psi^i=-(1+\tau)/\tau, \Psi^{-i}=1/\tau$, $\Psi^{i,i}=\Psi^{-i,-i}=-1/\tau^2$, and $\Psi^{i,-i}=1/\tau^2$.

All Ψ's have the same values as those based on the CES and duopolistic competition model ($n=2$) when $\sigma-1=2/\tau$. This is consistent with the finding by Anderson et al. (1992). However, there is a key difference: Demand depends on prices and is kinked in the Hotelling address model. When the deviation of p_t^i from p_t^{-i} is large and positive (negative), demand becomes zero (saturated) as $x_t^i=0$ (M_t/p_t^i). This leads to a mixed strategy when τ is heterogeneous, as discussed in Section 3.

2.2. Steady state without price stickiness

We consider the steady state in the case of no price stickiness. Firm i's profit is given by $\Pi_t^i=(p_t^i-W_t)x^i(p_t^i/M_t,p_t^{-i}/M_t)$. The first-order condition with respect to p_t^i yields

$$p=\Psi^i/(\Psi^i+1), \tag{1}$$

where we assume that the steady state is given by $W=M=1$.

Around the steady state, the slope of the best response price is given by $\partial\log p^i/\partial\log p^{-i}=\Psi^{i,-i}/\left\{\Psi^i(1+\Psi^i)\right\}$, which is positive in the CES oligopolistic competition model with $\sigma>1$ and finite n and in the Hotelling duopolistic competition model. This suggests static strategic complementarity. By contrast, the slope is negative in the CES oligopolistic competition model when $\sigma<1$ and n is finite. No strategic complementarity or substitutability exists in the CES monopolistic competition model ($n\to\infty$) because $\Psi^{i,-i}=0$. In Appendix A, we provide a comparison table regarding demand elasticities, the steady-state price, and the slope of the best response price for a general model, CES preferences based on monopolistic competition, CES preferences based on oligopolistic competition, kinked demand, and the Hotelling address model.

[5] The (Hotelling, 1929) part of the model in this study is based on the model presented by Armstrong (2006). Accordingly, we replicate Armstrong's results in the model without sticky prices.

2.3. Pricing under price stickiness

Hereafter, we consider the case of duopolistic competition $n = 2$. We assume Calvo-type price stickiness. Both firms A and B can reset their prices with a probability of $1 - \theta \in (0, 1)$.[6] In Appendix C, we confirm the robustness of our results by introducing Rotemberg-type price stickiness. We limit our analysis by assuming that the Markov perfect equilibrium concept applies. Each firm's action (i.e., price setting decision) depends on a state consisting only of the following three variables: its price in the previous period, the rival firm's price in the previous period, and a shock to money supply growth. We exclude collusive pricing, although the folk theorem suggests that dynamic settings can generate multiple collusive equilibria. The Calvo-type signal of price resetting is uncorrelated across product lines $j \in [0, 1]$.

When firm i has a chance to set its price at t, it sets $\bar{p}_t^i$ to maximize

$$\max \sum_{k=0}^{\infty} \theta^k \beta^k \mathbb{E}_t \left[\left(\bar{p}_t^i - W_{t+k} \right) \theta^{k+1} x^i (\bar{p}_t^i / M_{t+k}, p_{t-1}^{-i} / M_{t+k}) \right] \cdot \frac{\Lambda_{t+k}}{\Lambda_t} \frac{P_t}{P_{t+k}}$$
$$+ \sum_{k=0}^{\infty} \theta^k \beta^k \mathbb{E}_t \left[\left(\bar{p}_t^i - W_{t+k} \right) \sum_{k'=0}^{k} (1-\theta) \theta^{k-k'} x^i (\bar{p}_t^i / M_{t+k}, p_{t+k'}^{-i} / M_{t+k}) \right] \cdot \frac{\Lambda_{t+k}}{\Lambda_t} \frac{P_t}{P_{t+k}}, \tag{2}$$

where Λ_t represents the stochastic discount factor given by C_t^{-1}. Solving this optimization problem is more complex than solving a similar problem in a standard New Keynesian model based on monopolistic competition, because we have to explicitly consider the path of the prices set by the rival firm. Note that the rival firm's price p_{t+k}^{-i} equals $\bar{p}_{t+k}^i$ with the probability of $1 - \theta$; $\bar{p}_{t+k-1}^i$ with the probability of $\theta(1-\theta)$; $\cdots$; $\bar{p}_t^i$ with the probability of $\theta^k(1-\theta)$; and p_{t-1}^i with the probability of θ^{k+1} for $k \geq 0$.

Firm i has to consider how its reset price at t influences the rival firm's reset price at $t + k'$, which is given by $\partial \log \bar{p}_{t+k'}^{-i} / \partial \log \bar{p}_t^i$. Given the Markov perfect equilibrium, the log-linearized policy function for the optimal reset price is expressed in the following forms:

$$p_t^{i*} = \Gamma \hat{p}_{t-1}^i + \Gamma^* \hat{p}_{t-1}^{-i} + \Gamma^{\varepsilon} \varepsilon_t, \tag{3}$$

$$\partial \log \bar{p}_{t+k}^{-i} / \partial \log \bar{p}_t^i = \Gamma^* \text{ for } k \geq 1, \tag{4}$$

where $\bar{p}_t^i \equiv p M_t e^{p_t^{i*}}$, $p_t^i \equiv p M_t e^{\hat{p}_t^i}$. Firms A and B set their prices simultaneously so that neither firm knows whether the rival resets its price in the current period. Therefore, the optimal reset price is written as a function of prices not in the current period but in the previous period. Furthermore, firm A's value is influenced by firm B's reset price in the current period if resetting occurs, and firm B's reset price is influenced by firm A's price in the previous period. Therefore, firm A's optimal reset price depends on its own price in the previous period. Further, the optimal reset price depends on a stochastic aggregate shock in the current period.

The coefficients Γ and Γ^* show the elasticity of the optimal price in the current period with respect to a change in own price and the rival's price, respectively, in the previous period. Particularly, Γ^* is an important parameter that shows the degree of dynamic strategic complementarity if it is positive. The coefficient ($\Gamma^* = \partial \log \bar{p}_{t+k}^{-i} / \partial \log \bar{p}_t^i$) is independent of the period elapsed after price revision k and aggregate state ε_{t+k} because we consider a case in which the price of firm i is unchanged at $\bar{p}_t^i$ from t and a log-linearized economy around a steady state, respectively. The coefficient Γ^{ε} shows the elasticity of the optimal price with respect to the money supply growth shock. A smaller Γ^{ε} means that the price reacts less strongly to the money supply growth shock, amplifying the real effect of monetary policy.

The first-order condition for the optimal $\bar{p}_t^i$ enables us to solve p, Γ, Γ^*, and Γ^{ε} using the method of undetermined coefficients from the coefficients of 1, $\hat{p}_{t-1}^i$, $\hat{p}_{t-1}^{-i}$, and ε_t. We provide a detailed description in Proposition 1 in Appendix A. Here, for an illustration, we assume that the money supply growth shock is zero (i.e., $\mu_t = 0$ and $M_t = 1$). Focusing on the term that relates to the dynamic strategic complementarity effect, we express the first-order condition of Eq. (2) as follows:

$$0 = g(\bar{p}_t^i, \hat{p}_{t-1}^{-i}) + \sum_{k=1}^{\infty} \theta^k \beta^k \left(\bar{p}_t^i - 1 \right) \mathbb{E}_t \left[\sum_{k'=1}^{k} (1-\theta) \theta^{k-k'} \frac{\partial x^i (\bar{p}_t^i, p_{t+k'}^{-i})}{\partial p_{t+k'}^{-i}} \frac{\partial p_{t+k'}^{-i}}{\partial \bar{p}_t^i} \right]$$
$$= g(\bar{p}_t^i, \hat{p}_{t-1}^{-i}) + \sum_{k=1}^{\infty} \theta^k \beta^k \left(\frac{\bar{p}_t^i - 1}{\bar{p}_t^i} \right) \mathbb{E}_t \left[\sum_{k'=1}^{k} (1-\theta) \theta^{k-k'} x_{t+k}^i (\bar{p}_t^i, \bar{p}_{t+k'}^{-i}) \frac{\partial \log x^i (\bar{p}_t^i, \bar{p}_{t+k'}^{-i})}{\partial \log (\bar{p}_{t+k'}^{-i})} \frac{\partial \log p_{t+k'}^{-i}}{\partial \log \bar{p}_t^i} \right]$$

[6] In this type of model, firms have to optimize their reset price by taking into account the fact that their reset price today influences the optimal reset price in the future. Below, we consider the effects of this only to the extent that a firm's reset price today influences the rival firm's reset price in the following periods. The effect of a firm's reset price today on its own reset price in the following periods does not matter for its own pricing decision today, as the marginal change of firm value to a change in its own reset price in the following periods is zero.

$$\simeq g(p_t^{i*},\hat{p}_{t-1}^{-i})+\sum_{k=1}^{\infty}\theta^k\beta^k\left(1-\frac{1}{p}+p_t^{i*}\right)\mathbb{E}_t\left[\sum_{k'=1}^{k}(1-\theta)\theta^{k-k'}\underbrace{\left\{1+\Psi^i p_t^{i*}+\Psi^{-i}p_{t+k'}^{-i*}\right\}}_{x_{t+k}^i}\underbrace{\left\{\Psi^{-i}+\Psi^{i,-i}p_t^{i*}+\Psi^{-i,-i}p_{t+k'}^{-i*}\right\}}_{\Psi^{-i}}\cdot\Gamma^*\right],$$

where $g(\cdot)$ represents other terms. Both p_t^{i*} and $p_{t+k'}^{-i*}$ can be expressed using $\hat{p}_{t-1}^i$ and $\hat{p}_{t-1}^{-i}$ and terms higher than the first order, such as $\left(p_t^{i*}\right)^2$ and $p_t^{i*}p_{t+k'}^{-i*}$, can be neglected. Thus, the right-hand side of the equation is given by a linear combination of 1, $\hat{p}_{t-1}^i$, and $\hat{p}_{t-1}^{-i}$. In the model, firms conjecture that competitors are implementing strategies with first-order terms. Thus, the derivative of $\partial \log p_{t+k'}^{-i}/\partial \log \bar{p}_t^i$ becomes a constant (Γ^*), which shows up in the above equation in combination with the first-order approximation of $x_{t+k}^i\Psi^{-i}$. Specifically, a coefficient on 1 depends on Γ^* as well as p, which suggests that steady-state price is influenced by a degree of dynamic strategic complementarity. Further, it should be noted that if firms were allowed to conjecture that competitors were implementing strategies with second-order terms, then the derivative of $\partial \log p_{t+k'}^{-i}/\partial \log \bar{p}_t^i$ would be expressed in the first order, which would show up in the second-order approximation in combination with the second-order approximation of $x_{t+k}^i\Psi^{-i}$.

The following lemma shows how steady state p depends on the degree of dynamic strategic complementarity Γ^*.

Lemma 1. *The steady-state price under price stickiness equals*

$$p = 1-\left\{1+\Psi^i+\frac{\theta\beta(1-\theta)}{1-\theta^2\beta}\Psi^{-i}\Gamma^*\right\}^{-1}. \tag{5}$$

All proofs are presented in Appendix. This lemma shows that unless Γ^* is zero, the steady state under nominal rigidity is different from that without nominal rigidity. Firms take into account the effect of their price on the rival firm's price in the following periods. Specifically, if Γ^* is positive (dynamic strategic complementarity), an increase in firm A's price increases firm B's price in the following periods. This effect increases the steady-state price level. The above equation also shows that the steady-state price level becomes identical to that in the scenario without nominal rigidity in the limit of $\theta \to 0$. When $\Gamma^* = 0$, then $p = \Psi^i/(\Psi^i+1)$. Specifically, in the CES and monopolistic competition model, $p = \sigma/(\sigma-1)$.

This result is essentially the same as in Proposition 4 in Wang and Werning (2022).[7] At the first glance, one may interpret Proposition 4 in Wang and Werning (2022) as the equation that shows how Γ^* is determined by the demand elasticity and *observed* steady-state markup p. This expression is used for an empirical purpose, which we will discuss in the next section. As Wang and Werning (2022) note, both p and Γ^* are endogenous, depending on demand parameters Ψ's.

While the above lemma shows how steady-state price p is determined by Γ^*, the next lemma shows how Γ^* is determined by demand.

Lemma 2. *When $p \simeq /\Psi^i(\Psi^i+1)$, the degree of dynamic strategic complementarity Γ^* satisfies*

$$(\Psi^{i,-i}-\Psi^{-i})\left(\frac{\theta\beta}{1-\theta\beta}-\frac{\theta^2\beta}{1-\theta^2\beta}\right)\Gamma^{*2}+(\Psi^{-i}\Psi^{-i}+\Psi^{-i,-i})\mathbb{\Gamma}_{k1}^{-i}\Gamma^*+\Psi^{i,-i}\left(\frac{\theta}{1-\theta^2\beta}+\mathbb{\Gamma}_{k0}^{-i}\right) = \frac{1}{1-\theta\beta}\left(\Psi^i(\Psi^i+1)-\Psi^{i,i}\right)\Gamma^*, \tag{6}$$

where $\mathbb{\Gamma}_{k0}^{-i}$ is the second row and the second column of the following matrix:

$$(1-\theta)\Gamma[I-(\mathbb{\Gamma}/\theta)]^{-1}\left[\frac{1}{1-\theta^2\beta}I-\mathbb{\Gamma}/\theta[I-(\theta\beta\mathbb{\Gamma})]^{-1}\right]$$

$$\text{and } \mathbb{\Gamma} = \begin{pmatrix}\Gamma & \Gamma^* & \Gamma^\varepsilon\\ \Gamma^* & \Gamma & \Gamma^\varepsilon\\ 0 & 0 & \rho\end{pmatrix}.$$

Two results emerge from Lemma 2. First, when cross elasticity is zero ($\Psi^{-i}=0$), no dynamic strategic complementarity exists, that is, $\Gamma^*=0$. Second, except for special cases such as $\Psi^{-i}=0$, the solution of Γ^* is not expressed in a closed form because the $\mathbb{\Gamma}_{k0}^{-i}$ term in the above equation depends on Γ and Γ^ε. However, Γ^* can be approximated to a closed form when $|\mathbb{\Gamma}_{k0}^{-i}|$ is sufficiently small, as is shown in the following corollary.

[7] Equality holds when $(\lambda+\rho)/\lambda = \theta\beta(1-\theta)/(1-\theta^2\beta)$ and $(n-1)\Psi^{-i} = -(1+\Psi^i)$, where λ and ρ represent the Calvo and discount parameters, respectively, in continuous time (equivalent to θ and β).

Corollary 1. *Assume* $p \simeq /\Psi^i(\Psi^i+1)$, $|\Gamma_{k0}^{-i}| \ll 1, \beta \simeq 1$, $(n-1)\Psi^{-i} = -(1+\Psi^i)$, *and* $\Psi^{i,i} = \Psi^{-i,-i} = -\Psi^{i,-i} \simeq -(\Psi^{-i})^2$. *Then, dynamic strategic complementarity* Γ^* *is approximated as*

$$\Gamma^* = \frac{n-1+\left((n-1)^2+1\right)\Psi^{-i} - \sqrt{\left(n-1+\left((n-1)^2+1\right)\Psi^{-i}\right)^2 - 4(\Psi^{-i}-1)\left(\frac{\theta}{1+\theta}\right)^2\Psi^{-i}}}{2(\Psi^{-i}-1)\frac{\theta}{1+\theta}}. \tag{7}$$

Further, assume $n=2$ *and define* $\Psi^{i,i} = -(\Psi^{-i})^2 - \gamma^{i,i}\Psi^{-i}$, *and* $\Psi^{i,-i} = (\Psi^{-i})^2 + \gamma^{i,-i}\Psi^{-i}$, *where* $|\gamma^{i,i}, \gamma^{i,-i}| \ll 1$. *Then,* $\Gamma^* > 0$, $\partial\Gamma^*/\partial\Psi^{-i} > 0, \partial\Gamma^*/\partial\gamma^{i,i} < 0$ *and* $\partial\Gamma^*/\partial\gamma^{i,-i} > 0$ *when* $\Psi^{-i} > 0$, $\Psi^{-i} \neq 1$, *and* $\theta/(1+\theta) \simeq 1/2$. *When* $\Psi^{-i} < 0$ *and* $|\Psi^{-i}| \ll 1$, $\Gamma^* < 0$.

Note that we have $\Psi^i = -1 - \Psi^{-i}$, $\Psi^{i,i} = \Psi^{-i,-i} = -\Psi^{i,-i} = -(\Psi^{-i})^2$ in the duopolistic ($n=2$) CES/Hotelling models. In the latter part of the corollary, we allow a slight deviation for superelasticity $\Psi^{i,i}$ and $\Psi^{i,-i}$ by degree γ to investigate their effects on Γ^*.

This corollary indicates the following properties: First, a positive cross elasticity Ψ^{-i} yields dynamic strategic complementarity, whereas a negative cross elasticity (when the size is not too large) yields dynamic strategic substitutability. A positive (negative) cross elasticity means that demand increases (decreases) as the rival increases its price. Thus, under positive (negative) cross elasticity, when the rival sets a higher price in the previous period, it causes a firm to increase (decrease) its price in the current period. Second, dynamic strategic complementarity decreases as the absolute value of own superelasticity $|\Psi^{i,i}|$ increases. Quasi kinked demand (Kimball, 1995) is interpreted as an increase in $|\Psi^{i,i}|$, which is often considered to cause an increase in dynamic strategic complementarity. However, what we present here is the opposite: It decreases dynamic strategic complementarity. The third property is that an increase in cross superelasticity $\Psi^{i,-i}$ increases dynamic strategic complementarity. Cross superelasticity is likely positive, suggesting that own demand becomes more elastic as the rival's price decreases. Thus, if a firm anticipates that its rival's price will be low, the firm will prefer to keep its price low. By contrast, if the rival's price is high, the absolute size of own demand elasticity decreases, which causes the firm to increase its price. This is indeed dynamic strategic complementarity. The second and third results show that an increase in cross superelasticity, rather than the absolute size of own superelasticity, is necessary to increase dynamic strategic complementarity.

Corollary 1 is in line with Online Appendices D and E in Wang and Werning (2022), which present the system of equations to solve the steady-state price (p) and the degree of dynamic strategic complementarity (Γ^*). Our method of log-linearization is equivalent to their approximation of a locally linear equilibrium ($m=2$), where the policy function for the optimal price ($g(p)$) is linear (i.e., $g^{(k)}(p) = 0$ for $k \geq m$), and demand elasticity matters up to the second order (superelasticity). One difference is that the optimal reset price in our model depends on a firm's own price in the previous period, the rival's price in the previous period, and the aggregate shock in the current period, whereas that in Wang and Werning (2022) depends only on the rival's price in the current period because there is no aggregate shock and time is continuous in their study. Consequently, the response to an aggregate shock is explicitly expressed in our study as Γ^ε. The second difference is that we derive a closed-form solution to Γ^*, albeit an approximation. Although Proposition 4 in Wang and Werning (2022) is a closed form, this is essentially the equation that is used to indicate how steady-state price p is determined after we know Γ^*, and not how Γ^* is determined. Third, we show that an increase in superelasticity does not necessarily increase dynamic strategic complementarity, although (Wang and Werning, 2022) demonstrate that an increase in superelasticity increases the half-life of the price level adjustment through an increase in dynamic strategic complementarity. Our analysis shows that it is important to separate own and cross superelasticities, and an increase in own superelasticity decreases dynamic strategic complementarity.

2.4. Numerical illustrations

We solve p, Γ, Γ^*, and Γ^ε numerically without resorting to the approximation given by Eqs. (6) or (7). A time unit is a quarter. We calculate demand parameters Ψ's using transport cost $\tau = 0.125$ based on the Hotelling model such that the steady-state markup without price stickiness is consistent with that based on the CES monopolistic competition model with $\sigma = 9$, as assumed by Gali (2015). This value of τ is equivalent to $\sigma = 17$ in the CES duopolistic competition model. Price stickiness is set at $\theta = 0.75$, which implies that price revisions occur once per year. We also use $\rho = 0.85$ and $\beta = 0.99$.

Policy Function

To derive Corollary 1, we assumed $p \simeq /\Psi^i(\Psi^i+1), |\Gamma_{k0}^{-i}| \ll 1$, $\beta \simeq 1$, $(n-1)\Psi^{-i} = -(1+\Psi^i)$, and $\Psi^{i,i} = \Psi^{-i,-i} = -\Psi^{i,-i} \simeq -(\Psi^{-i})^2$. If these assumptions were invalid, the difference between the numerical calculation and analytical approximation would be large. Based on the numerical calculation, the coefficient of dynamic strategic complementarity Γ^* on the policy function for the optimal reset price equals 0.218, while the approximation given by Eq. (7) in Corollary 1 yields 0.209, which is close. Thus, the conditions imposed in Corollary 1 are more or less satisfied and the error from using this approximation appears to be small. In Appendix A, we confirm that the approximation error is small for a wide parameter region.

Figure 1 shows policy functions for the optimal reset price, specifically, coefficients Γ^* and Γ^ε in Eq. (3). We change one of the five parameter values that characterize demand, Ψ^i, Ψ^{-i}, $\Psi^{i,i}/|\Psi^i|$, $\Psi^{-i,-i}/|\Psi^{-i}|$, $\Psi^{i,-i}/\sqrt{/|\Psi^i\Psi^{-i}|}$, while keeping the other four parameter values fixed.

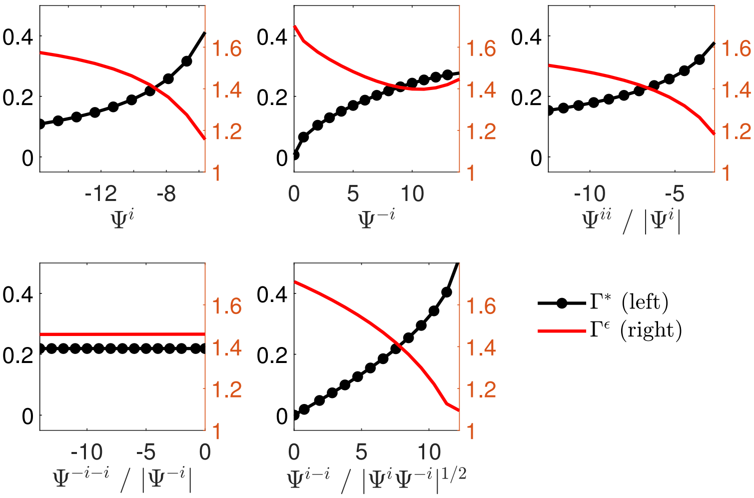

Fig. 1. Policy Functions under Price Stickiness: Dependence on Demand Elasticities. *Note:* The figure shows the coefficients of policy functions for the optimal reset price by firm A (specifically Γ^* and Γ^ε) given by $p_t^{A*} = \Gamma \hat{p}^A_{t-1} + \Gamma^* \hat{p}^B_{t-1} + \Gamma^\varepsilon \varepsilon_t$ when we change one of the five elasticity parameter values (own Ψ^i, cross Ψ^{-i}, own super $\Psi^{i,i}/|\Psi^i|$, $\Psi^{-i,-i}/|\Psi^{-i}|$, and cross super $\Psi^{i,-i}/\sqrt{/|\Psi^i\Psi^{-i}|}$), while keeping the other four parameter values fixed.

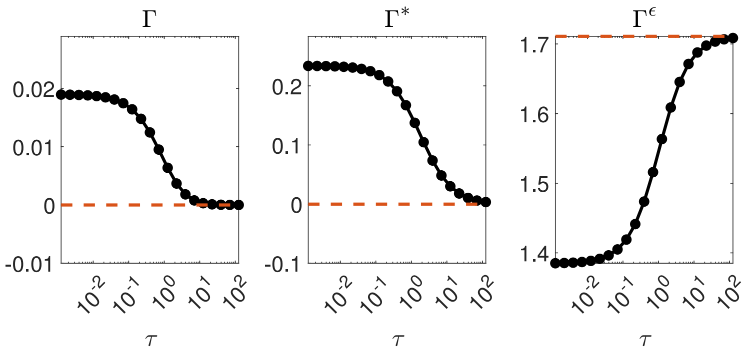

Fig. 2. Policy Functions under Price Stickiness: Dependence on Transport Costs. *Note:* The figure shows the coefficients of policy functions for the optimal reset price by firm A given by $p_t^{A*} = \Gamma \hat{p}^A_{t-1} + \Gamma^* \hat{p}^B_{t-1} + \Gamma^\varepsilon \varepsilon_t$. The horizontal axis represents the transport cost based on the Hotelling model (τ, log scale), which is equivalent to the elasticity of substitution with $\sigma = 1 + 2/\tau$ based on the CES duopolistic competition model. The dashed line represents the coefficients of policy functions for the CES monopolistic competition model ($n \to \infty$ and $\sigma = 9$).

This figure suggests that Γ^* is positive (i.e., dynamic strategic complementarity exists), and it increases as own elasticity $|\Psi^i|$ decreases, cross elasticity Ψ^{-i} increases, own superelasticity $|\Psi^{i,i}/\Psi^i|$ decreases, or cross superelasticity $\Psi^{i,-i}/\sqrt{/|\Psi^i\Psi^{-i}|}$ increases. This result is consistent with Corollary 1.

Figure 1 also indicates that the response to aggregate shock, Γ^ε, tends to move in the opposite direction to Γ^*. This implies that dynamic strategic complementarity increases price sluggishness and the real effect of monetary policy.

Although it is useful to show how each of the demand parameters Ψ's influences policy functions Γ^* and Γ^ε, demand parameters are not independent of one another. Thus, we consider how a single parameter, given by transport cost τ based on the Hotelling model, influences policy functions by affecting Ψ's. Recall that the model is equivalent to the CES duopolistic competition model with the elasticity of the substitution of $\sigma = 1 + 2/\tau$.

Figure 2 shows policy functions; for comparison, we plot herein the policy functions in the CES monopolistic competition model ($n \to \infty$) with $\sigma = 9$. The figure shows that both Γ and Γ^* are positive. This suggests that a firm revises its price upward when its previous price was high (i.e., $\Gamma > 0$) or its rival's previous price was high (i.e., $\Gamma^* > 0$). Quantitatively, the size of Γ^* is around 10 times larger than the size of Γ, showing that a firm's own past price is much less important than its rival firm's price. While Γ and Γ^* increase, Γ^ε decreases relative to that in the CES monopolistic competition model. The price responds to an aggregate shock to a lesser extent, which increases the real effect of monetary policy.

Figure 3 shows how the number of firms n influences policy functions. Our analysis assumes a duopolistic competition because otherwise, the timing of other firms' price resetting becomes heterogeneous under Calvo-type price stickiness. If one assumes that all other firms reset their prices simultaneously with a probability of $1 - \theta$, then the following results hold for any $n \geq 2$. Based on the CES oligopolistic competition model with $\sigma = 1 + 2/\tau = 17$, we change n, which is a proxy

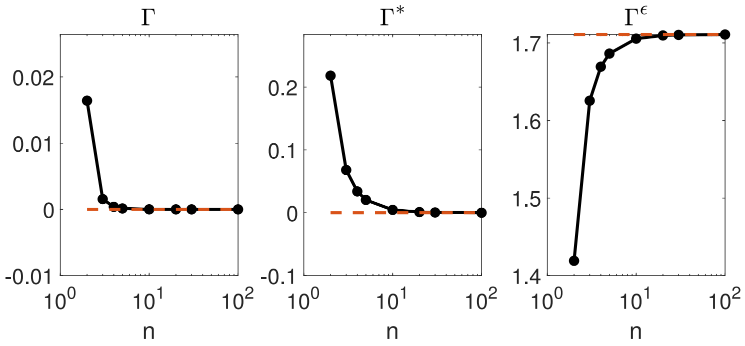

Fig. 3. Policy Functions under Price Stickiness: Dependence on the Number of Firms. *Note:* The figure shows the coefficients of policy functions for the optimal reset price by firm A given by $p_t^{A*} = \Gamma \hat{p}_{t-1}^A + \Gamma^* \hat{p}_{t-1}^B + \Gamma^\varepsilon \varepsilon_t$. The horizontal axis represents the number of firms in an industry (n, log scale) based on the CES oligopolistic competition model. The dashed line represents the coefficients of policy functions for the CES monopolistic competition model ($n \to \infty$ and $\sigma = 9$).

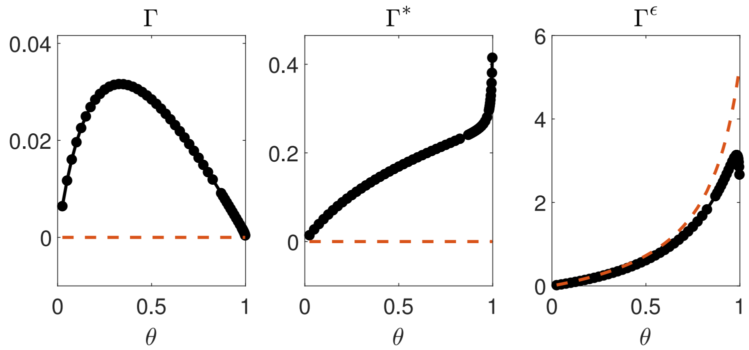

Fig. 4. Policy Functions under Price Stickiness: Dependence on Price Stickiness. *Note:* The figure shows the coefficients of policy functions for the optimal reset price by firm A given by $p_t^{A*} = \Gamma \hat{p}_{t-1}^A + \Gamma^* \hat{p}_{t-1}^B + \Gamma^\varepsilon \varepsilon_t$. The horizontal axis represents price stickiness (θ). The dashed line represents the coefficients of policy functions for the CES monopolistic competition model ($n \to \infty$ and $\sigma = 9$).

for market concentration, from 2 to 100. The figure shows that Γ and Γ^* decrease as n increases, whereas Γ^ε increases with n. The degree of dynamic strategic complementarity and the real effect of monetary policy are the largest when n is 2.

Figure 4 presents policy functions, where the horizontal axis represents price stickiness θ. The figure shows that both Γ and Γ^* are positive unless $\theta = 0$, and they depend on the value of θ. Specifically, Γ^* increases monotonically as θ increases, showing that an increase in price stickiness increases the degree of dynamic strategic complementarity. By contrast, the response of Γ to θ is not monotonic: Γ increases with θ when θ is small; however, when θ is around 0.75, Γ decreases with θ. The size of Γ^ε increases with θ, suggesting that price stickiness increases the price response to an aggregate shock.

Steady-State Price

The dynamic strategic complementarity owing to a positive Γ^* leads to a higher markup in the steady state under sticky prices, as illustrated in Eq. (5). Figure 5 shows the steady-state price under sticky prices. The steady-state price is plotted as a ratio to the price under flexible prices given by Eq. (1). In the three panels, we show the steady-state price by changing the parameter values of transport cost τ, the number of firms n, and the degree of price stickiness θ.

Transport cost τ influences the steady-state price in a non-monotonic manner. There are two forces. On the one hand, a high τ increases the steady-state price under flexible prices. Specifically, when τ is zero, firms earn no markup, and thus, price stickiness does not matter for the ratio of the steady-state price under sticky prices to that under flexible prices. On the other hand, a high τ weakens dynamic strategic complementarity (i.e., Γ^* decreases as τ increases). As a result of Eq. (5), this decreases the steady-state price under sticky prices. Consequently, there is a certain τ that maximizes the ratio of the steady-state price under sticky prices relative to that under flexible prices. For $\tau = 0.125$, the steady-state price p under sticky prices is larger by around 1% compared with that under flexible prices. In other words, the markup $(p - 1)$ increases from 12.5% to 13.8%.

The steady-state price increases as the number of firms n decreases to two. This does not stem from an increase in the steady-state markup under flexible prices as the figure shows a ratio of the price under sticky prices to the price under flexible prices. As n decreases, dynamic strategic complementarity Γ^* increases, which increases the steady-state price under sticky prices from Eq. (5).

For the influence of the degree of price stickiness θ, there is a certain θ that maximizes the ratio of the steady-state price under sticky prices to that under flexible prices. When θ is not too high, an increase in θ magnifies the importance

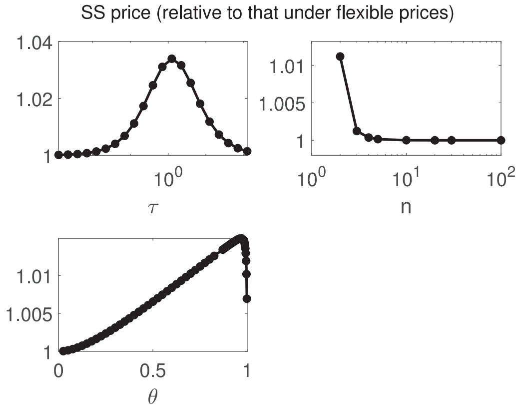

Fig. 5. Steady-State Price under Price Stickiness. *Note:* The vertical axis represents the ratio of the steady-state (SS) price under sticky prices to that under flexible prices.

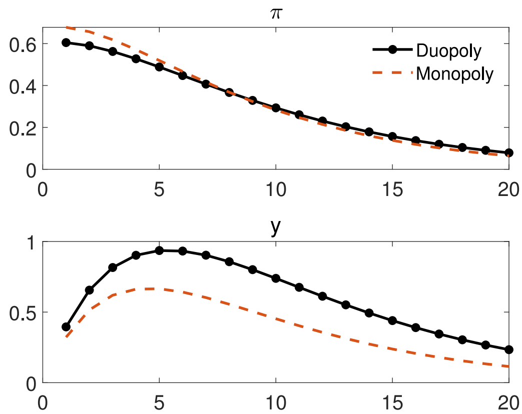

Fig. 6. Impulse Responses to Money Supply Growth Shock. *Note:* The horizontal axis represents quarters after a positive money supply growth shock occurs at $t = 1$..

of reacting to $\hat{p}^B_{t-1}$ for firm A because firm B is more likely to keep its price unchanged. This strengthens dynamic strategic complementarity and, in turn, increases the steady-state price under sticky prices. However, when θ is very large, firm A's price today is less likely to influence firm B's price tomorrow because firm B is less likely to reset its price. This weakens the effect of dynamic strategic complementarity and, in turn, decreases the steady-state price under sticky prices.

Impulse Responses

Figure 6 shows the impulse response functions to a positive money supply growth shock ($\mu_t = 1$ at $t = 1$) for aggregate inflation rate π_t and output $\hat{Y}_t$. While the nominal effect of monetary policy on inflation is smaller, the real effect of monetary policy in this model is larger than that in the New Keynesian model based on monopolistic competition by approximately 50%. This is due to the dynamic strategic complementarity of price setting, as explained above. Firms react to the monetary policy shock by taking their rivals' pricing into account strategically, which reduces the size of price adjustments (i.e., Γ^{ε} decreases). This increases aggregate price stickiness, which increases the real effect of monetary policy.

3. Mixed-strategy pricing under duopolistic competition and nominal stickiness

In this section, we investigate the possibility of accounting for temporary sales (price discounts) as a mixed strategy and then the effect of monetary policy in the presence of temporary sales. See Appendix D for details.

We assume two firms ($i = A, B$) and consider an arbitrary invertible demand system $x^i_t = x^i(p^i_t/M_t, p^{-i}_t/M_t)$ for $i = A, B$. We allow demand elasticities to depend on prices so that firms may set two possible prices, namely, higher p_H (with the probability of $1 - s$) and lower p_L (with the probability of s), as a mixed strategy. Firm profit is given by $\Pi^i_t = (p^i_t - W_t)x^i(p^i_t/M_t, p^{-i}_t/M_t)$, and the expected demand after choosing p_t is given by $(1 - s)x(p_t/M_t, p_H/M_t) + sx(p_t/M_t, p_L/M_t)$. We define own and cross elasticities, which depend on a firm's own price and the rival's price, as $\Psi^i(p^i/M, p^{-i}/M) \equiv \frac{\partial \log x^i(p^i/M, p^{-i}/M)}{\partial \log(p^i/M)}$ and $\Psi^{-i}(p^i/M, p^{-i}/M) \equiv \frac{\partial \log x^i(p^i/M, p^{-i}/M)}{\partial \log(p^{-i}/M)}$, respectively. Whether elasticities depend on the rival's price is particularly important for the mixed strategy.

3.1. Steady state without price stickiness

Pure Strategy

First, we consider a steady state without price stickiness. One possible option for a pricing strategy is a pure strategy. The prices of firms A and B are symmetric, $p^* = p^A = p^B$, which satisfies $p^* = \Psi^i(p^*, p^*)/(\Psi^i(p^*, p^*) + 1)$.

Under some conditions, a firm may have an incentive to deviate and choose p^d. For example, in the Hotelling model, given firm B's price p^*, firm A may be able to increase its profit by giving up revenues from price-sensitive bargain hunters and charging a higher price. The condition for the pure strategy equilibrium to hold is written as $\Pi^i(p^*, p^*) > \Pi^i(p^d, p^*)$ for any p^d.

Mixed Strategy

If there exists a mixed strategy equilibrium, the first-order conditions with respect to p_H and p_L should be zero for $p_H > p_L$; that is, $\partial\Pi^i/\partial p^H = \partial\Pi^i/\partial p^H = 0$, yielding

$$0 = (1-s)x^{HH}\left\{1 + (p_H - 1)\frac{\Psi^i(p_H, p_H)}{p_H}\right\} + sx^{HL}\left\{1 + (p_H - 1)\frac{\Psi^i(p_H, p_L)}{p_H}\right\} \tag{8}$$

$$0 = (1-s)x^{LH}\left\{1 + (p_L - 1)\frac{\Psi^i(p_L, p_H)}{p_L}\right\} + sx^{LL}\left\{1 + (p_L - 1)\frac{\Psi^i(p_L, p_L)}{p_L}\right\}, \tag{9}$$

where $x^{ij} \equiv x(p_i, p_j)$ for $i, j = H$ or L. Furthermore, the expected profits from choosing the higher price, $\Pi_H(p_H, p_L, s) \equiv \Pi(p_H|p_H, p_L, s)$ and the lower price $\Pi_L(p_H, p_L, s) \equiv \Pi(p_L|p_H, p_L, s)$ should be equal:

$$\begin{aligned}\Pi_H(p_H, p_L, s) &\equiv (p_H - 1)\left\{(1-s)x^{HH} + sx^{HL}\right\}\\ &= (p_L - 1)\left\{(1-s)x^{LH} + sx^{LL}\right\} \equiv \Pi_L(p_H, p_L, s).\end{aligned} \tag{10}$$

These three equations yield steady-state p_H, p_L, and s. We obtain the following corollaries.

Corollary 2. *When own demand elasticity is independent of prices, a mixed strategy equilibrium does not arise.*

When $\Psi^i(p_H, p_H) = \Psi^i(p_H, p_L)$, $\Psi^i(p_L, p_H) = \Psi^i(p_L, p_L)$, $x^{HL} = x^{HH}$, and $x^{LH} = x^{LL}$, a mixed strategy equilibrium does not arise either.

This corollary suggests that a mixed strategy equilibrium does not arise in a model based on CES preferences. Even in the presence of consumer heterogeneity, a mixed strategy equilibrium does not arise as long as aggregate demand elasticity (the sum of consumer demands) is constant. Furthermore, even if own demand elasticity depends on prices, a mixed strategy equilibrium does not arise when own demand and its elasticity are independent of the rival's price.

The next corollary shows that a mixed strategy may entail two kinds of strategic complementarity.

Corollary 3. *Assume that a mixed strategy equilibrium exists. Then, $p_H(p_L, s)$ obtained from Eq. (8) satisfies $\partial p_H/\partial p_L > 0$ unless $\Psi^{i,-i}(p_H, p_L)$ is too large.*

Assume $x^{HH} > x^{HL}$ and $x^{LH} > x^{LL}$. Then, $\frac{\partial\Pi_H(p_H, p_L, s)}{\partial s} < 0$ and $\frac{\partial\Pi_L(p_H, p_L, s)}{\partial s} < 0$. If $x^{LH} - x^{HH} \gtreqless x^{LL} - x^{HL}$, then $\frac{\partial\Pi_H(p_H, p_L, s)}{\partial s} - \frac{\partial\Pi_L(p_H, p_L, s)}{\partial s} \lesseqgtr 0$.

The first line of the corollary suggests that the higher price exhibits strategic complementarity with the lower price. For the second line of the corollary, the assumption of $x^{HH} > x^{HL}$ and $x^{LH} > x^{LL}$ is standard. This corollary shows that an increase in the frequency of sales decreases the firm profit, irrespective of whether the firms choose the higher price. More importantly, it shows that as the frequency of sales increases, the profit from choosing the higher price decreases more than that from choosing the lower price when $x^{LH} - x^{HH} > x^{LL} - x^{HL}$. Thus, this increases the incentive to choose the lower price, which implies strategic complementarity in temporary sales. The condition $x^{LH} - x^{HH} > x^{LL} - x^{HL}$ means that an increase in demand by choosing the lower price given that the rival sets the higher price is greater than an increase in demand by choosing the lower price given that the rival sets the lower price. When the condition is reversed (i.e., $x^{LH} - x^{HH} < x^{LL} - x^{HL}$), the profit from choosing the lower price decreases more than that from choosing the higher price. Thus, there is strategic substitutability in temporary sales.

It should be noted that these two kinds of strategic complementarity concern the interaction between setting the higher price on the one hand and setting the lower price or the frequency of temporary sales on the other. There is the third kind of strategic complementarity, which concerns the interaction between two firms' higher prices.

Hotelling Address Model

In the Hotelling address model with heterogeneous τ, a mixed strategy equilibrium may arise. Specifically, we incorporate consumers' heterogeneity in terms of not only their location (x) but also their transport cost (τ): Some consumers may have access to a car and be more mobile, whereas others may not, because, for example, they are elderly, unhealthy, or busy working (see Armstrong 2006). Note that transport cost τ also represents a consumer's choosiness. Thus, the heterogeneity of τ also indicates how some consumers are loyal to a particular firm (brand) (i.e., price-insensitive), whereas others are bargain hunters (i.e., price-sensitive). Then, the former customers have higher τ than the latter. Specifically, τ takes τ_L with the probability of α or τ_H otherwise ($0 < \tau_L < \tau_H$). This probability is independent of consumer location. Firms A and B cannot observe consumers' transport cost, but they have accurate knowledge about the distribution characterized by τ_H, τ_L, and α.[8] Appendix D.2 explains the details of pure and mixed strategy equilibria and the welfare implications.

We have the following corollary as a special case of Corollary 3.

Corollary 4. *Assume that a mixed strategy equilibrium exists in the Hotelling address model with heterogeneous transport costs. Then, $p_H(p_L, s)$ obtained from Eq. (8) satisfies $\partial p_H/\partial p_L > 0$. Moreover, $\frac{\partial \Pi_H(p_H,p_L,s)}{\partial s} - \frac{\partial \Pi_L(p_H,p_L,s)}{\partial s} < 0$.*

The second property of Corollary 4 is markedly different from that reported by Guimaraes and Sheedy (2011). They argue that sales show strategic substitutability; that is, if other firms choose a higher price rather than a lower price more frequently, a firm will be better off if it chooses a lower price rather than a higher price more frequently.

The difference in the strategic property can be understood as follows: First, in their model, firms are monopolistic rather than duopolistic. Thus, firms do not make strategic pricing decisions. Second, Guimaraes and Sheedy (2011) assume that there exist two types of consumers whose elasticities of substitution differ but are constant. As shown above, the CES preference does not yield a mixed strategy. Strictly speaking, two price equilibria in Guimaraes and Sheedy's (2011) study are not mixed strategy equilibria as in our model. In their model, each firm can set multiple prices in each period, choosing a higher price for a certain fraction of products and a lower price for the other.

3.2. Pricing under price stickiness

In the next step, we add Calvo-type price stickiness. Both firms A and B compete in multiple periods and can reset their prices at the probability of $1-\theta \in (0,1)$.

Pure Strategy

First, we consider a case in which the pure strategy equilibrium holds. Importantly, the condition for the pure strategy equilibrium to hold, which was shown in the previous subsection, is relaxed. In the dynamic setup where two firms compete repeatedly, the incentive to deviate from the pure strategy decreases. Nevertheless, we can obtain the implications of price stickiness, which are similar to those in Section 2.3. We obtain the following lemma.

Lemma 3. *Suppose that the pure strategy equilibrium holds. The steady-state price under price stickiness p equals*

$$p = 1 - \left\{1 + \Psi^i(p,p) + \frac{\theta\beta(1-\theta)}{1-\theta^2\beta}\Psi^{-i}(p,p)\Gamma^*\right\}^{-1}. \tag{11}$$

Mixed Strategy

We introduce additional assumptions for the mixed strategy case. First, the lower price $p_{L,t}$ is perfectly flexible and set at $p_L W_t$, where p_L denotes the steady-state lower price when $W_0 = 1$. Second, the Calvo-type lottery determines either the higher price or the frequency of sales as the variable that firms can reoptimize. With the probability of $1-\theta$, firms can revise the higher price, and in this case, firms cannot optimize the frequency of sales. We explain the details of these assumptions in Appendix D.3. Admittedly, these assumptions are restrictive, and thus, we will examine how a different assumption regarding the frequency of sales changes our results.

Based on an arbitrary invertible demand system, we obtain the following lemma, which is related to Lemma 1 in the case of pure strategy.

Lemma 4. *Suppose that the mixed strategy equilibrium holds. The steady-state price under price stickiness p_H satisfies*

$$\begin{aligned}&\frac{p_H-1}{p_H}\left\{s x_{HL}\Psi^i_{HL} + (1-s)/2\Psi^i_{HH} + (1-s)/2\frac{\theta\beta(1-\theta)}{1-\theta^2\beta}\Psi^{-i}_{HH}\Gamma^* + \theta^2\beta s\Lambda^{n*}\left(x^i_{HL}-1/2\right)\right\}\\ &= -(s x_{HL} + (1-s)/2),\end{aligned} \tag{12}$$

where $\Gamma^* \equiv \partial\log\bar{p}^{-i}_{H,t+k}/\partial\log\bar{p}^i_{H,t}$ and $\Lambda^{n*} \equiv \partial\log s^n_{t+k}/\partial\log\bar{p}^i_{H,t}$ for $k \geq 1$.

Remarks on Empirical Work

The above equation can be transformed into

$$\Gamma^* = -\left\{\left(\frac{p_H}{p_H-1} + \Psi^i_{HH}\right) + \frac{s}{1-s}2p_H x_{HL}\left(\frac{p_H}{p_H-1} + \Psi^i_{HL}\right) + \frac{s}{1-s}\theta^2\beta\Lambda^{n*}\left(2p_H x^i_{HL} - 1\right)\right\}\left\{\frac{\theta\beta(1-\theta)}{1-\theta^2\beta}\Psi^{-i}_{HH}\right\}^{-1}. \tag{13}$$

Four observations can be made from this equation. First, this equation confirms Wang and Werning's (2022) remark. Regressing a measure of non-neutrality of money (Γ^*) on average markups (p_H), controlling for concentration, should yield a

[8] If firms A and B can observe each consumer's transport cost, they set their price differently: $p = (1+\tau_L/2)W$ for consumers with τ_L and $p = (1+\tau_H/2)W$ for consumers with τ_H. In other words, firms charge a higher price for price-insensitive loyal consumers and a lower price for price-sensitive bargain hunters.

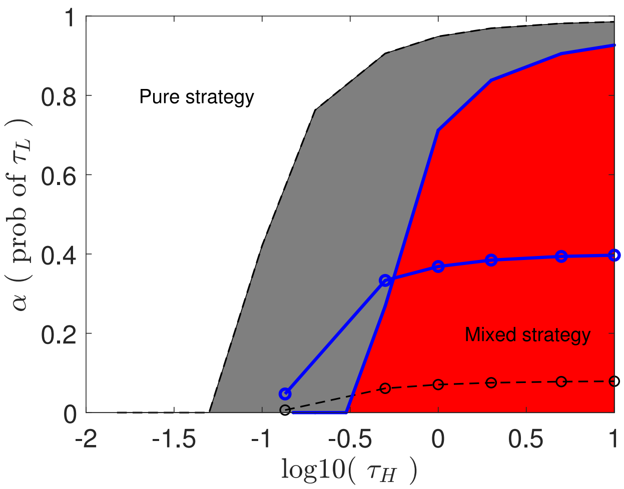

Fig. 7. Equilibrium Region under Consumer Heterogeneity and Flexible Prices. *Note:* The thin dashed line (in black) and the thick solid line (in blue) represent the boundary between the pure and mixed strategies when the parameter τ_L is set at 0.01 and 0.05, respectively. The thick solid line with circles (in blue) and the thin dashed line with circles (in black) indicate the combination of τ_H and α that keeps the harmonic mean of τ at 0.125, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

positive coefficient even in the presence of temporary sales unless Λ^{n*} is negative and large. Further, extending Wang and Werning's (2022) remark, we can argue that regressing a measure of non-neutrality of money (Γ^*) on average markups (p_H), the frequency of sales (s), and their cross term ($p_H s$), while controlling for concentration, should yield a positive, ambiguous, and positive coefficient, respectively. The coefficient on s is positive (negative) if $p_H/(p_H-1)+\Psi^i_{HL}$ is positive (negative), that is, when the absolute own elasticity is small (large).

Second, this equation implies the existence of a bias in the evaluation of dynamic strategic complementarity Γ^* by ignoring temporary sales. Suppose that one incorrectly evaluates Γ^* (denoted by Γ^*_{pure}) from Eq. (11) based on the pure strategy equilibrium that ignores temporary sales. Further, we assume that one uses only the higher price p_H as a proxy for p. Then, the biased Γ^*_{pure} is evaluated as

$$\Gamma^*_{pure} = -\left(\frac{p_H}{p_H-1}+\Psi^i_{HH}\right)\left\{\frac{\theta\beta(1-\theta)}{1-\theta^2\beta}\Psi^{-i}_{HH}\right\}^{-1}. \tag{14}$$

Two values of Γ^* and Γ^*_{pure} deviate from the second and third terms in the numerator for the equation of Γ^*. Given a mixed strategy, the deviation increases as the frequency of sales s increases or when the gap $p_H/(p_H-1)+\Psi^i_{HL}$ is large. In Section 3.3, we evaluate the size of the bias numerically.

Third, Eq. (13) shows that the degree of dynamic strategic complementarity may decrease. If firm B sets the lower price, only price-insensitive consumers purchase from firm A when firm A sets the higher price, which makes demand more inelastic when there is a possibility of temporary sales than when there is only a pure strategy equilibrium. This, in turn, decreases the degree of dynamic strategic complementarity.

To calculate the mixed strategy equilibrium, we need to solve the steady state under sticky prices, p_H, p_L, s, and the policy function up to the first order characterized by, for example, Γ^*, Γ^ε, and Λ^{n*}. We provide a detailed description of the mixed strategy equilibrium based on the Hotelling model as Proposition 2 in Appendix D.4.

3.3. Numerical illustrations

For the simulation, we use the parameter values explained in Section 2.4. The only exception is the transport cost. Instead of the homogeneous value of $\tau=0.125$, we use various combinations for the values of τ_H, τ_L, and α.

Pure and Mixed Strategy Region under Flexible Prices

We show numerical results under flexible prices (i.e., $\theta\to 0$). First, Fig. 7 illustrates the parameter region in which the equilibrium is characterized by either the pure or mixed strategy. We fix τ_L at either 0.01 or 0.05. The figure shows that the pure strategy equilibrium is more likely to arise as the difference between τ_L and τ_H becomes smaller (i.e., τ_L is larger and τ_H is smaller) or the probability of τ_L becomes higher. The mixed strategy equilibrium is more likely to arise in the opposite case. The line with circles shows the combination of τ_H and α, which is required to keep the harmonic mean of τ at 0.125. This line intersects with the boundary at the point dividing the pure and mixed strategy equilibria. This suggests that if a harmonic mean-preserving difference for τ_H and τ_L exceeds a certain level, the equilibrium changes from the pure strategy equilibrium to the mixed strategy equilibrium.

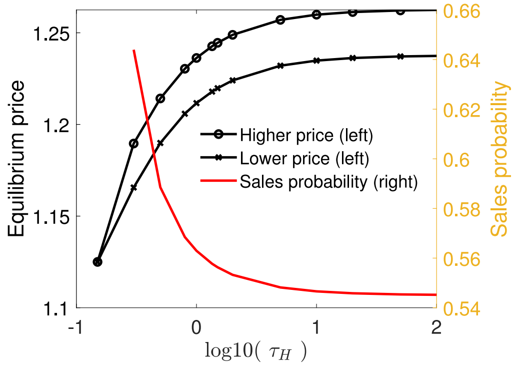

Fig. 8. Equilibrium Price under Consumer Heterogeneity and Flexible Prices. *Note:* The parameter τ_L is set at 0.01, and α is chosen to keep the harmonic mean of τ at 0.125.

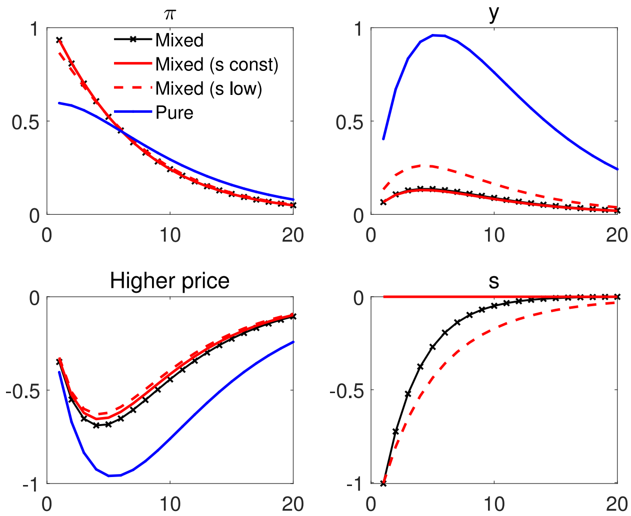

Fig. 9. Impulse Responses to Money Supply Growth Shock. *Note:* For the pure strategy, τ is homogeneous and equals 0.125. For the mixed strategy, τ_L and τ_H equal 0.01 and 1, respectively, whereas parameter α is chosen to make the harmonic mean of τ equal 0.125 (i.e., $\alpha = 0.07$). Mixed (s low) represents the case in which the frequency of sales (s) is around 15%, whereas Mixed (s const) represents the case in which s is kept constant.

Second, Fig. 8 shows how the equilibrium price changes when τ_H changes. Here, we fix τ_L at 0.01 and adjust α so that the harmonic mean of τ is unchanged at 0.125. When τ_H is low (close to τ_L), the pure strategy constitutes the equilibrium, and the equilibrium price is independent of τ_H because the harmonic mean of τ is unchanged. When τ_H is high, the mixed strategy constitutes the equilibrium, generating two possible equilibrium prices. The figure shows that compared with the pure strategy, the mixed strategy leads to higher equilibrium prices. Interestingly, the equilibrium price is higher even for the lower price of the two. As τ_H increases (i.e., the harmonic mean-preserving difference increases), the two equilibrium prices increase. Meanwhile, the probability of sales (i.e., the probability of choosing the lower price rather than the higher price) decreases. It should also be noted that in this model, the size of the sale discount, $(p_H - p_L)/p_H$, is approximately 15%, whereas the frequency of sales is around 60%. Compared with the data (e.g., see Sudo et al., 2018), the former is almost the same, but the latter is considerably higher. The frequency of sales decreases if we allow the own demand elasticity to be smaller than that based on the Hotelling model when both firms A and B set the price around the lower price, which we will discuss in the next analysis.

Mixed Strategy under Sticky Prices and Impulse Responses

Next, we simulate the model under price stickiness ($\theta = 0.75$). We set τ_L and τ_H at 0.01 and 1, respectively, whereas α is chosen to make the harmonic mean of τ equal to 0.125 (i.e., $\alpha = 0.07$). In this case, the mixed strategy serves as the equilibrium. We calculate policy functions numerically with respect to pricing and then calculate the impulse responses to a positive money supply growth shock ($\mu_t = 1$ at $t = 1$).

The solid line with the cross in Fig. 9 shows the simulation results. All the variables are log-linearized from their steady-state values.[9] The figure shows that a positive money supply growth shock increases the inflation rate and output. The

[9] The lower left-hand panel shows the log-linearized aggregate higher price. Specifically, by denoting the log-linearized optimal reset higher price by p_t^*, we can express the aggregate higher price in period t as $\hat{p}_t = \theta(\hat{p}_{t-1} - \varepsilon_t) + (1-\theta)p_t^*$.

higher price is negative, suggesting that price stickiness prevents some firms from adjusting their price upward. Meanwhile, these firms optimally adjust the frequency of sales; specifically, they decrease it.

For comparison, we plot the impulse responses when τ is homogeneous at 0.125 as the line. In this case, equilibrium is characterized by the pure strategy. Although the inflation rate and output exhibit the same qualitative pattern, the magnitude of the change in output is considerably different. Namely, the output under the mixed strategy increases by less than one-tenth.

The real effect of monetary policy decreases for the following three reasons: first, because the degree of dynamic strategic complementarity for setting the higher price Γ^* decreases. Demand becomes more inelastic when there is a possibility of temporary sales than when there is only a pure strategy equilibrium, which decreases the degree of dynamic strategic complementarity. Numerically, we obtain $\Gamma^* = -0.09$, which suggests dynamic strategic substitutability, rather than complementarity, under the mixed strategy equilibrium. It should also be noted that if we assume a pure strategy equilibrium incorrectly and calculate Γ^* from Eq. (14), we obtain $\Gamma^*_{pure} = 1.11$, suggesting that ignoring sales results in a huge bias.

Second, instead of decreasing, the degree of dynamic strategic complementarity increases for the interaction of the setting of the higher and lower prices. The lower left-hand panel shows that although the aggregate higher price under the mixed strategy is negative, the extent to which it deviates from the steady state is smaller than the extent to which the aggregate price deviates under the pure strategy. Under the mixed strategy, the lower (i.e., sale) price is revised upward fully in response to the positive money supply growth shock. Combined with the first type of strategic complementarity effect shown in Corollary 4, this induces firms to increase their higher price more when they can reset it. Furthermore, owing to the second type of strategic complementarity effect shown in Corollary 4, a greater increase in the lower price than in the higher price increases the expected profit from setting the lower price. To maintain profit equality, the frequency of sales needs to decrease. This decrease in the frequency of sales increases the aggregate price. Therefore, nominal prices are adjusted upward more strongly, which weakens the real effect of monetary policy.

Third, sales are assumed to be perfectly flexible, and the frequency of sales is high in our model. For robustness, we set the own demand elasticity when both firms A and B set the price around p_L at -50, which is smaller than $-\mathbb{E}[1/\tau] - 1 = -9$ based on the Hotelling model (see Appendix D.1). Then, the frequency of sales decreases from 60% to 15%, which is comparable to the value based on the data. Note that this change in own demand elasticity affects only the first-order condition with respect to p_L and not the first-order condition with respect to p_H or the equation for the profit indifference between choosing p_H and p_L. The dashed line in Fig. 9 shows that the real effect of monetary policy remains substantially small, although the decrease in the frequency of sales increases the real effect of monetary policy relative to the benchmark case of a mixed strategy when the frequency of sales is 60%.

Recall that we assume a certain constraint that prevents firms from optimizing both the higher price and the frequency of sales simultaneously. Firms optimize the frequency of sales only when they cannot revise their higher price. To investigate the quantitative importance of this assumption, in Fig. 9, we also demonstrate simulation results when the frequency of sales is kept constant. Technically, we assume that the equality of profits from choosing the higher price and lower price does not necessarily hold except in the steady state. The figure shows that although the frequency of sales does not decrease in response to the shock, the other three variables (i.e., the inflation rate, output, and higher price) hardly change.

This result is markedly different from that reported by Guimaraes and Sheedy (2011). In their model, the existence of temporary sales hardly changes the real effect of monetary policy. Sales exhibit strategic substitutability; that is, if other firms choose a higher price rather than a lower price more frequently, a firm will be better off if it chooses a lower price rather than a higher price more frequently. This leads to a result wherein the real effect of monetary policy hardly changes despite sales.

4. Concluding remarks

In this study, we provided a tractable macroeconomic model incorporating duopolistic competition and price stickiness. We found that implications for monetary policy change when we incorporate the strategic pricing behaviors of oligopolistic firms. Firms' pricing entails a dynamic (intertemporal) strategic complementarity. The optimal reset price positively depends on the price set by the rival firm in the previous period. This property increases the real effect of monetary policy slightly, relative to that in a standard monopolistic competition model in which strategic complementarity is absent. However, when a mixed strategy equilibrium arises, the real effect of monetary policy is weakened considerably.

It will be interesting to see how a model extension can help connect recent developments regarding firm dynamics (e.g., an increase in markup and a decrease in business dynamism) with those regarding inflation dynamics (e.g., a decrease in the inflation rate in developed countries and the disappearing Phillips curve).

Data Availability

No data was used for the research described in the article.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jmoneco.2023.01.003.

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