Journal of Monetary Economics 63 (2014) 64–79

Contents lists available at ScienceDirect

Journal of Monetary Economics

journal homepage: www.elsevier.com/locate/jme

Central bank communication design in a Lucas-Phelps economy ☆

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ARTICLE INFO

Article history:
Received 15 February 2012
Received in revised form
22 January 2014
Accepted 23 January 2014
Available online 2 February 2014

Keywords:
Lucas-Phelps island economies
Public and private information
Coordination in beauty-contest games
Optimal announcements
Central bank design

ABSTRACT

In a Lucas-Phelps island economy, an island has access to many informative signals about demand conditions. Each signal incorporates both public and private information: the correlation of a signal's realizations across the economy determines its publicity. If information sources differ in their publicity then price-formation and expectations-formation processes separate, causing output gaps to open. An output-stabilizing central bank prefers "averagely public" information, and sometimes limits the clarity of its policy announcements to achieve this. The bank's incentive to engage privately in costly information acquisition and transmission is strongest not for the most influential signals, but instead for those which drive the largest wedge between prices and expectations: signals that are far from averagely public.

1. Public announcements and transparency

Consider a Lucas-Phelps island economy with supply-side uncertainty over economy-wide prices, and demand-side uncertainty over an underlying fundamental. In such an economy, heterogeneous beliefs generate variation in real prices and outputs. For the communication design of an output-stabilizing planner (a central bank) two questions are considered. Firstly, what are the ideal characteristics of informative announcements? Secondly, if commitment to an ideal announcement is impossible then how should the bank allocate its costly resources to the acquisition and transmission of information?

Briefly, the answers are these. Firstly, an ideal announcement is "averagely public" in the sense that interpretations of it should be correlated but not perfectly so. This implies that it is neither optimal to withhold information entirely, nor is it optimal to release perfectly transparent information. Secondly, if commitment to an averagely public signal is impossible then the incentives for a central bank to acquire and transmit information are not necessarily strongest for the channels which have the most influence on prices; instead, the bank should focus on those which open the largest gaps between the price-setting and expectation-formation processes. Such gaps arise from channels which are far from averagely public in nature. In summary, the bank prefers to commit to averagely public announcements, but in the absence of commitment it diverts resources elsewhere.

☆ Earlier versions of this article were circulated under the titles "On the Sources and Value of Information: Public Announcements and Macroeconomic Performance" and "On the Sources and Value of Information: Publicity and Performance in a Lucas-Phelps Island Economy."

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0304-3932/$ - see front matter
http://dx.doi.org/10.1016/j.jmoneco.2014.01.003

Communication is part of contemporary thinking about central bank design. A recent paper by Reis (2013) discusses 12 principles of such a design. Three of those principles concern the importance of announcements and commitments; the extent of transparency; and the choice of communication channels. His discussion of communication channels notes that the Federal Reserve, for example, has a decentralized structure which "makes it harder for agents to coordinate on the public signals provided by policy." Such a structure, then, helps to commit the bank to avoiding perfect publicity.

These principles are also of direct concern to central bankers. The Bank of England's Monetary Policy Committee recently published a document describing its commitment to forward guidance (Bank of England, 2013). The "Design Considerations" section (p. 23) describes four criteria for economic indicators. For three of these, they note that indicators need "to provide a good guide to the broad economic conditions," they worry "how likely are they to provide a misleading signal," and they recognize "some data are less volatile, or less subject to revision, than are others." Each of these reflects an indicator's ability to identify correctly economic conditions. The Bank's fourth criterion asks: "how easy are [the data] to communicate?" For instance, when discussing the possible use of the output gap (p. 26) they note it is "difficult to explain" and "subject to substantial uncertainty." This is all in the context of an indicator's influence on higher-order expectations and the Bank's objectives: they emphasize (p. 37) "the responsiveness of medium-term inflation expectations to news about the economic outlook" and (p. 1) "the desirability of avoiding undue output volatility." Beyond the choice of indicators, other aspects of a central bank's design can influence the nature of its own informative announcements. For example, expanding its research staff might aid the underlying quality of its information, whilst hiring an incoherent chair or governor could lower the clarity of its announcements.

Academic concern for the principles of central bank design and policymakers' focus on the choice of economic indicators motivate the key question of this study: how do the properties of information sources affect output stability and optimal communication?

Section 2 describes an island economy (Phelps, 1970; Lucas, 1972) with uncertainty over the prices on other islands and over an underlying fundamental. Each island receives (possibly many) signals of the fundamental and a local price equilibrates aggregate supply and demand. In doing so, the inhabitants evaluate not only their expectations of the fundamental, but also the expectations held elsewhere which determine economy-wide prices and so influence aggregate supply.

Morris and Shin (2002) considered a related model with two signals of this sort: one private (an independent signal realization for each sector) and one public (common knowledge to all). They argued that a social planner would sometimes (but not always) wish to suppress the public signal. Their insight was that a public signal exerts a disproportionately large influence: such a signal is particularly useful for the formation of higher-order expectations, since agents know that the inhabitants of other sectors have seen the same signal realization. This influential idea prompted a growing literature which often makes a hard-and-fast distinction between public and private information.

The information structure used here blunts this distinction. Each signal is characterized not only by its variance but also by its cross-sectoral correlation. Equivalently, a signal has both accuracy (signal quality) and transparency (signal clarity). A signal with imperfect quality (it imperfectly identifies the fundamental) but with perfect clarity (everyone sees the same thing) is "purely public" and is perfectly correlated across the economy. A signal with perfect quality but with imperfect clarity (islands observe different signal realizations, but the average is correct) is "purely private" and so (conditional on the fundamental) is uncorrelated. The model allows for a general (conditional) correlation coefficient for each of many signals and so intermediate values of "publicity" are feasible; equivalently, arbitrary mixes of signal quality and signal clarity are permitted.

The move to a more general information structure is important for (at least) three reasons. Firstly, comparative-static exercises that vary the precisions of public and private signals conflate two properties: the signal's quality in the first case, and its clarity in the second. Secondly, reducing the transparency of a public signal results in an imperfectly correlated signal: this is a step away from a "public and private" model. Thirdly, an assessment of a bank's communication policy must envisage at least three sources of information: agents' prior beliefs, any independent island-specific information, and the announcement itself.

Despite the step forward in generality, the equilibrium is characterized easily: the price in a sector is a weighted average of the signals received by its inhabitants (Section 3). The influence of a signal is increasing in its precision and its publicity, where a signal's publicity is a monotonic transformation of its cross-sectoral correlation; at the ends of the publicity spectrum lie purely private and purely public signals.

The reactions of output stability to signal precision and publicity are readily found. Relatively public signals do exert a disproportionate influence. Moreover, differences in the "publicity" of signals drive a wedge between the price-formation process and the expectations (or higher-order expectations)-formation process. It is this wedge which causes output gaps to open up on a given island. No matter how noisy signals (and hence prices) are, a gap will not open if the price-setting and expectation-formation processes remain synchronized. For instance, in a world with just a single signal (or many identically correlated signals) prices and expectations move together. Gaps arise when the correlation coefficients of signals differ since expectations react more strongly to relatively public signals than do prices. An insight is that what matters is differences in the publicity of information sources available to agents. Output gaps are shrunk by "averagely public" signals but are opened by both very public and very private ones.

The notion of publicity is central to the optimal communication policy of an output-stabilizing planner, such as a central bank (Section 4). For an information source whose technology enables it to be more public than average, the policy involves maximal quality but may involve reduced clarity. Indeed, if the technology is sufficiently public (this is so if commonly understood announcements are feasible), then the bank will certainly degrade the clarity of its signal. On the other hand, if the information source's technology is less public than average then the bank will maximize clarity but may degrade the quality (and will certainly do so if the technology is sufficiently private).

If the bank speaks clearly then its announcement will be relatively public. Heterogeneity in the publicity of signals drives apart the price-formation and expectation-formation processes, and so output stability can be enhanced by making the announcement less public. One way to do this is to muddy the communication process by adding noise. It is never optimal to suppress communication completely; once enough noise is added then the bank's signal becomes averagely public and so helps to unify prices and expectations. A symmetric logic applies to a relatively private information source.

The direct effect of obfuscation is to exacerbate output variability; any benefit arises indirectly from inducing greater emphasis on averagely public information. If the bank's actions are unobserved then this indirect effect disappears, and so it should again make full use of its technology. However, increasing either the quality or clarity of an information source is unlikely to be cost-free, and so the paper also considers (Section 5) the incentives to engage in costly information acquisition (improving the quality of an underlying signal) and transmission (improving the clarity with which it is communicated).

The endogenous publicity of the bank's signal is determined by the relative costliness of information acquisition versus transmission. Fixing this publicity, the overall incentive to engage in costly information provision is not necessarily strongest for those signals which have the most influence on prices. Noise does not matter whenever prices and expectation-processes move together (i.e. when the signal is "averagely public"). Prices and expectations diverge only if the information source is either very public or very private relative to the average. Here, increased noise is damaging for output variability, and so the bank faces strong incentives to reduce noise by improving both quality and clarity.

These incentives to reduce noise form jointly with the islands' pricing rules. There is thus a complementarity in the bank's choice of a signal's quality (or clarity) and its influence. When a signal is ignored, there is little incentive to improve its precision, reinforcing the tendency for prices to respond weakly to that signal. On the other hand, when acquisition and transmission costs are low, the bank might be expected to provide relatively precise information, increasing its incentives to do so and resulting in self-fulfilling (but costly) endogenous information acquisition. In such circumstances, the policy-maker may be better off if it were able to commit to releasing no information at all.

This research offers four contributions to the literature (described in Section 6). Firstly, it abandons the public-and-private signal taxonomy and develops the idea of a signal's publicity. This has notable consequences: publicity differences across information sources drive expectation-formation and price-formation processes apart. Secondly, it shows the importance of this feature in the context of a macroeconomic performance measure based on the output gap (emerging from the Lucas-Phelps island economy, rather than from the welfare of players in a related beauty-contest game). Thirdly, the paper re-examines public announcements: it illustrates how such announcements ought to vary with the nature of the economy's extant information. Finally, it highlights the incentives for a policy-maker to engage in costly information acquisition and transmission in such a setting.

2. A Lucas-Phelps island economy

This section specifies a Lucas-Phelps island economy and its associated information structure.

2.1. The island economy

The economy consists of a unit mass of "island" sectors indexed by $\ell \in [0,1]$. The (natural logarithm of) nominal price in sector ℓ is p_ℓ and the economy-wide aggregate price level is $\overline{p} = \int_0^1 p_l \, dl$. The natural level of economic activity is normalized so that its logarithm is zero. Activity in sector ℓ is y_ℓ which, given the normalization, is also the gap between output and capacity.

An economy-wide fundamental $\theta \in \mathbb{R}$ drives aggregate demand. As will become clear, if this fundamental were common knowledge then (in equilibrium) all prices would satisfy $p_\ell = \theta$ and output gaps would be eliminated. However, the inhabitants of each sector are uncertain of the fundamental and of the aggregate price level. They form expectations $\mathrm{E}_\ell[\theta]$ and $\mathrm{E}_\ell[\overline{p}]$, where the subscripts indicate expectations taken with respect to the (common) beliefs held in sector ℓ. Aggregate supply and demand in sector ℓ satisfy

$$y_{\ell S} = \alpha_S(p_\ell - \mathrm{E}_\ell[\overline{p}]) \quad \text{and} \quad y_{\ell D} = \alpha_D(\mathrm{E}_\ell[\theta] - p_\ell). \tag{1}$$

Equating supply and demand yields the market-clearing price p_ℓ in sector ℓ:

$$p_\ell = \pi \mathrm{E}_\ell[\theta] + (1-\pi)\mathrm{E}_\ell[\overline{p}] \quad \text{where } \pi = \frac{\alpha_D}{\alpha_S + \alpha_D}. \tag{2}$$

The market-clearing nominal price in sector ℓ combines expectations of the fundamental and of the economy-wide price level; the relative weight placed on these expectations depends on the slopes of aggregate supply and demand.

The pricing rule in (2) can be micro-founded. It applies when differentiated suppliers compete in prices à la Bertrand (Myatt and Wallace, 2012), and foundations can be derived from DSGE models (Angeletos and La'O, 2009; Angeletos et al., 2011); moving beyond pricing rules, the same structure arises from investment games with complementarities (Angeletos and Pavan, 2004) and in a Cournot game (Myatt and Wallace, 2013). Abstracting away from a specific micro-foundation, the focus here is on the role played by different types of information in the coordination problem.

A feature of this specification is that demand depends upon expectations of θ, where θ might be thought of as an idealized but unknown nominal anchor. Another possibility is for aggregate demand in each island to depend, perhaps noisily, on the fundamental itself. This would happen if $y_{\ell D} = \alpha_D(\theta_\ell - p_\ell)$ where θ_ℓ is an island-specific aggregate demand shock with mean θ. This alternative specification leads to some broadly similar results and insights, and is briefly discussed later in the paper. However, the main focus on expectations-driven demand facilitates a comparison with the existing literature.

For the Lucas-Phelps island interpretation, a natural macroeconomic performance measure is based upon output gaps. If θ were known then setting $p_\ell = \theta$ for all sectors would lead to $y_\ell = 0$, and hence no deviation from the natural level of activity. However, uncertainties over the fundamental and the aggregate price level allow gaps to open; indeed, $y_\ell \neq 0$ except in special circumstances. Aggregating across the islands and treating positive and negative gaps symmetrically suggests the use of $\int_0^1 y_l^2\, dl$. Ex ante this measure becomes $\mathrm{E}[y_\ell^2]$. The unique equilibrium characterized later in the paper has the feature that $\mathrm{E}[y_\ell] = 0$, and so $\mathrm{E}[y_\ell^2] = \mathrm{var}[y_\ell]$. Given that the model is specified in log terms, $\mathrm{var}[y_\ell]$ is an appropriate unit-free measure of the variability of output, and so $\mathrm{E}[y_\ell^2]$ can readily be used to assess output stability.[1]

As Morris and Shin (2002, 2005) noted, there is a connection between the island-economy model and a quadratic-payoff "beauty contest" game in which player $\ell \in [0,1]$ chooses an action $p_\ell \in \mathbb{R}$ and receives a payoff $u_\ell = \overline{u} - \pi(p_\ell - \theta)^2 - (1-\pi)(p_\ell - \overline{p})^2$. Taking expectations, the optimal action for player ℓ is $p_\ell = \pi \mathrm{E}_\ell[\theta] + (1-\pi)\mathrm{E}_\ell[\overline{p}]$. This is the market-clearing price from (2). This specification describes a potential game: players act as if they are jointly maximizing the potential function

$$\phi(p) = \overline{u} - \pi \int_0^1 (p_l - \theta)^2\, dl - (1-\pi) \int_0^1 (p_l - \overline{p})^2\, dl. \tag{3}$$

Notice that $\phi(p) = \int_0^1 u_l\, dl$ and so the potential function aggregates the players' payoffs; a consequence is that, in such a beauty contest, the equilibrium is efficient.[2]

2.2. Information

All islands share an improper common prior over θ. Any substantive prior belief can be accommodated via the specification of signals described below.

Island sector ℓ receives a vector $x_\ell \in \mathbb{R}^n$ of informative signals. Signals are independent across the n information sources. Fixing an information source $j \in \{1, \ldots, n\}$, however, the observations of different sectors are correlated. Conditional on θ, the signals observed are jointly distributed according to the normal, with common variance σ_j^2. Any pair of sectors ℓ and $\ell' \neq \ell$ have a correlation coefficient of ρ_j, so that

$$x_{j\ell} | \theta \sim N(\theta, \sigma_j^2) \quad \text{and} \quad \mathrm{cov}[x_{j\ell}, x_{j\ell'} | \theta] = \rho_j \sigma_j^2. \tag{4}$$

The informativeness of the jth source is indexed by its precision $\psi_j \equiv 1/\sigma_j^2$. Given the improper prior, the conditional expectation of the fundamental θ satisfies

$$\mathrm{E}[\theta | x_\ell] = \sum_{i=1}^{n} \overline{w}_i x_{i\ell} \quad \text{where } \overline{w}_j = \frac{\psi_j}{\sum_{i=1}^n \psi_i}. \tag{5}$$

If prices were determined only by this then only the precision ψ_j of a signal would be relevant. However, the price p_ℓ in sector ℓ depends upon expectations of economy-wide prices and so, implicitly, upon beliefs about the beliefs held in other sectors. This means that the commonality of signals, indexed by the correlation coefficient ρ_j, is also relevant.

This specification, proposed in a political-science context by Dewan and Myatt (2008), encompasses those used by Morris and Shin (2002, 2005), Angeletos and Pavan (2004, 2007), Hellwig (2005), and others. Most related work has considered games in which each player receives a public signal and a private signal. Here, a public signal is obtained by setting $\rho_j = 1$; the same realization is seen in every sector. A private signal, in contrast, corresponds to $\rho_j = 0$; conditional on the fundamental, it says nothing about other sectors. Only in recent research (Morris and Shin, 2007; Dewan and Myatt, 2008; Hellwig and Veldkamp, 2009; Angeletos and Pavan, 2009; Myatt and Wallace, 2012) have authors emphasized the use of imperfectly correlated signals; an exception is the supplementary material to Morris and Shin (2002), discussed in the online appendix, which reports a two-player model with partially correlated signals. The public–private taxonomy usefully highlights the role played by higher-order expectations; however, it misses interesting scenarios in which signals are correlated but imperfectly so.

[1] Output stability is not the only measure of macroeconomic performance that might be considered. The online appendix discusses how different measures relate to this.

[2] This does not apply to all equivalent beauty-contest specifications. Morris and Shin (2002), for instance, added a strategically irrelevant but welfare-relevant term $(1-\pi)\int_0^1 (p_l - \overline{p})^2\, dl$ to the payoff of player ℓ.

One such scenario is when the jth signal is provided by a sender of information; a central bank or a financial newspaper for example. The sender observes a noisy signal of θ,

$$\tilde{x}_j = \theta + \eta_j \quad \text{where } \eta_j \sim N(0, \kappa_j^2), \tag{6}$$

so that η_j is "sender noise" attributable to the information acquisition of the sender; the precision $1/\kappa_j^2$ measures the ability of the sender to identify θ. The sender then communicates the signal to the agents in the various sectors of the island economy. However, the agents in sector ℓ observe the signal imperfectly:

$$x_{j\ell} = \tilde{x}_j + \varepsilon_{j\ell} \quad \text{where } \varepsilon_{j\ell} \sim N(0, \xi_j^2), \tag{7}$$

so that $\varepsilon_{j\ell}$ is "receiver noise" from errors in the communication process; the precision $1/\xi_j^2$ measures the clarity of communication between sender and receiver. The various noise terms (η_j and $\varepsilon_{j\ell}$) are assumed to be independently distributed. Combining sender noise and receiver noise yields the specification of (4), where

$$\sigma_j^2 = \kappa_j^2 + \xi_j^2 \quad \text{and} \quad \rho_j = \frac{\kappa_j^2}{\kappa_j^2 + \xi_j^2}. \tag{8}$$

How informative a signal is for the identification of the fundamental depends only upon the total noise. However, the balance between sender noise and receiver noise influences the commonality of the views held in different island sectors.

The sender–receiver specification is recovered via $\kappa_j^2 = \rho_j \sigma_j^2$ and $\xi_j^2 = (1-\rho_j)\sigma_j^2$; similarly, (purely) public or (purely) private signals are obtained easily by setting either $\xi_j^2 = 0$ or $\kappa_j^2 = 0$. However, the sender–receiver model proves useful by illustrating the somewhat restrictive nature of the public–private classification.

To see this, begin with a central bank that communicates perfectly, so that $\xi_j^2 = 0$ and $\rho_j = 1$. Suppose now that it muddles its communications by transmitting via an imperfect channel. This corresponds to an increase in ξ_j^2, which in turn leads to $\rho_j \in (0,1)$. The signal received by the various island sectors is partially private, and partially public; the variance parameters κ_j^2 and ξ_j^2 indexing sender and receiver noise might equivalently be labelled as public and private noise. This parameter change seems to represent an interesting thought experiment, and yet it is excluded by (most) existing models.

Interior values of $\rho_j \in (0,1)$ generate partially public signals. Others have used different approaches. For example, Morris and Shin (2007) considered a "semi-public" specification: information receivers are divided into groups with signals that are exclusive to each group. Increasing the number of groups changes the "fragmentation" (in their terminology) of information; here, this corresponds to a change in ρ_j. More recently Chahrour (2013) considered the "scope" (in his terminology) and precision of public signals. In his setting, a social planner controls the number (that is, scope) and precision of perfectly public signals. In the absence of information-acquisition costs, scope and precision are equivalent. However, in his model scope is costly (for the planner's audience) whereas precision is not. There is an incentive for a social planner to limit scope in order to curtail the (excessive, relative to the social optimum) acquisition costs incurred by the audience.

3. Output stability in equilibrium

In this section the equilibrium pricing rule is characterized, and its properties explored.

3.1. Equilibrium

An equilibrium pricing rule for each island sector maps signal realizations to market-clearing prices, so that $p_\ell = P_\ell(x_\ell) : \mathbb{R}^n \mapsto \mathbb{R}$. Since sectors are symmetric and each sector is negligible, it is without loss of generality to restrict attention to symmetric pricing rules so that $p_\ell = P(x_\ell)$ for all $\ell \in [0,1]$. Condition (2) reduces to

$$P(x_\ell) = \pi \mathrm{E}[\theta | x_\ell] + (1-\pi)\mathrm{E}[P(x_{\ell'})|x_\ell]. \tag{9}$$

For general signal specifications an equilibrium pricing rule takes an arbitrary form. However, as is now well known, the adoption of normal distributions for signals ensures that there is a unique linear equilibrium. That is, for some set of weights $w \in \mathbb{R}_+^n$,

$$P(x_\ell) = \sum_{i=1}^n w_i x_{i\ell} \quad \text{where } \sum_{i=1}^n w_i = 1, \tag{10}$$

so that the price in a sector is a weighted average of the signals seen by its inhabitants. This is to be expected since the regressions $\mathrm{E}[\theta|x_\ell]$ and $\mathrm{E}[x_{\ell'}|x_\ell]$ are both linear in their conditioning arguments. That is, $\mathrm{E}[\theta|x_\ell] = a \cdot x_\ell$ for some vector a where "$\cdot$" indicates the usual vector product, and $\mathrm{E}[x_{\ell'}|x_\ell] = Bx_\ell$ for the $n \times n$ inference matrix B. Similarly, writing w for the vector of weights with jth element w_j, and restricting attention to the class of linear equilibria, the market-clearing condition (9) for each sector reduces to

$$w \cdot x_\ell = \pi a \cdot x_\ell + (1-\pi) w \cdot Bx_\ell \Leftrightarrow w = \pi[I - (1-\pi)B']^{-1} a. \tag{11}$$

The linear equilibrium may be characterized by solving (11) directly.[3] However, it is rather more straightforward to utilize the fact (Section 2) that the isomorphic beauty contest is an exact potential game. This means that the equilibrium weights w successfully maximize the ex ante expectation of $\phi(p)$ in (3). Writing expectations operators in place of integrals and with $p_\ell = w \cdot x_\ell$, the equilibrium weights minimize

$$\pi \mathrm{E}[(p_\ell - \theta)^2] + (1-\pi)\mathrm{E}[(p_\ell - \overline{p})^2] \tag{12}$$

subject to $\sum_{i=1}^n w_i = 1$. Note that $\sum_{i=1}^n w_i = 1$ is not an exogenous restriction; the set of coefficients must satisfy this equality if it is to successfully maximize the expected potential.[4] Consider the first element in (12). Since the weights add to one,

$$\mathrm{E}[(p_\ell - \theta)^2] = \sum_{i=1}^n w_i^2 \mathrm{E}[(x_{i\ell} - \theta)^2] = \sum_{i=1}^n w_i^2 \sigma_i^2 = \sum_{i=1}^n w_i^2 (\kappa_i^2 + \xi_i^2), \tag{13}$$

where the second equality follows from (4) and the third from (8). The second element may be expressed in a similar way. First, note that $\overline{p} \equiv \int_0^1 p_l \, dl = \int_0^1 \sum_i w_i x_{il} \, dl = \sum_i w_i \tilde{x}_i$, so that the expected price level across sectors is the weighted sum of the senders' observations as defined in (6). Now the second key element of (12) is

$$\mathrm{E}[(p_\ell - \overline{p})^2] = \sum_{i=1}^n w_i^2 \mathrm{E}[(x_{i\ell} - \tilde{x}_i)^2] = \sum_{i=1}^n w_i^2 \xi_i^2, \tag{14}$$

where the second equality follows directly from the specification given in (7). Collecting these two elements together again, the minimization programme can be restated as

$$\min_w \sum_{i=1}^n w_i^2 (\pi \kappa_i^2 + \xi_i^2) \quad \text{such that} \quad \sum_{i=1}^n w_i = 1. \tag{15}$$

Solving this latter problem is straightforward and yields the weights w for the linear equilibrium pricing rule of (10). Note that the weight attached to each information source j depends on the correlation of signals received by different sectors of the island economy. More emphasis is placed on receiver noise (or errors in communication) than on sender noise (errors in the senders' observation of the fundamental).

To see why this is so, recall that market-clearing prices satisfy (2), so that $p_\ell = \pi \mathrm{E}_\ell[\theta] + (1-\pi)\mathrm{E}_\ell[\overline{p}]$. (Analogously, players of a beauty-contest game aim to be close to both the fundamental and the aggregate action of others.) Receiver noise frustrates both of these objectives; however, sender noise moves a sector away from the fundamental but does not move p_ℓ away from the economy-wide average $\overline{p}$. Since adherence to the fundamental carries a reduced weight of π, so too does the corresponding sender-noise term κ_j^2.

Proposition 1. *There is a unique equilibrium pricing rule $P(x_\ell) = \sum_{i=1}^n w_i x_{i\ell}$, satisfying*

$$w_j = \frac{\psi_j \beta_j}{\sum_{i=1}^n \psi_i \beta_i} \quad \text{where } \beta_j = \frac{1}{1 - \rho_j (1-\pi)}. \tag{16}$$

The relative influence of an information source increases with its precision and with the correlation of signals that different sectors receive. Equivalently, since

$$\psi_j \beta_j = \frac{1}{\pi \kappa_j^2 + \xi_j^2}, \tag{17}$$

the influence of an information source decreases with both sender noise and receiver noise. Across information sources, if $\rho_j > \rho_{j'}$, the influence of j relative to j' increases as π falls.[5]

β_j is a natural measure of the "publicity" of a signal j. As discussed earlier, a purely public signal of the sort considered in the literature corresponds to $\rho_j = 1$, which means $\beta_j = 1/\pi$. On the other hand, purely private information yields $\rho_j = 0$ and $\beta_j = 1$. Between these bounds, publicity increases with correlation. Moreover, β_j depends upon the importance of coordination, measured by $(1-\pi)$. As greater emphasis is placed on coordination (so that π falls; this happens when the Lucas supply function becomes shallower) the influence of the most public signals rises at the expense of the least public signals.

[3] The restriction to linearity in (11) is not quite without loss of generality. Recursive application of (9) as proposed by Morris and Shin (2002) does not establish uniqueness, as explained by Angeletos and Pavan (2007, footnote 5) and others. The linear equilibrium is unique in a class of appropriately bounded equilibrium pricing rules; this is discussed briefly in the online appendix. Linear equilibria are in any case rather natural and, following in the footsteps of the earlier literature, are the focus here.

[4] The ex ante expectation of $\phi(p)$ remains finite if and only if $\sum_{i=1}^n w_i = 1$. In any case, this equality emerges readily from the familiar method of matching coefficients which yields (11).

[5] Aggregate demand is driven indirectly by beliefs about the fundamental. If instead demand is driven directly by θ, so that $y_{\ell D} \propto \theta_\ell - p_\ell$, then a variant of Proposition 1 holds; see the online appendix.

A signal's publicity is central to its influence, and the signals' publicities are also critical for the analysis of output stability considered in the next section. For the results that follow, two different notions of average publicity are important:

$$\overline{\beta} \equiv \sum_{i=1}^{n} w_i \beta_i = \frac{\sum_{i=1}^{n} \psi_i \beta_i^2}{\sum_{i=1}^{n} \psi_i \beta_i} \quad \text{and} \quad \hat{\beta} \equiv \frac{\sum_{i=1}^{n} \psi_i \beta_i}{\sum_{i=1}^{n} \psi_i} \tag{18}$$

where $\overline{\beta}$ is the equilibrium-weighted average publicity, in which the importance of a signal is determined by its influence in equilibrium. In contrast, $\hat{\beta}$ is the precision-weighted average publicity, where the weights used are those which correspond to the formation of the conditional expectation of θ. It is straightforward to confirm that $\overline{\beta} \geq \hat{\beta}$.

3.2. *Output stability*

The focus of this section is the relationship between output stability and the properties of the various informative signals. Note that in equilibrium

$$y_{\ell D} = \alpha_D(\mathrm{E}_\ell[\theta] - p_\ell) \Rightarrow y_\ell \propto (\mathrm{E}[\theta | x_\ell] - P(x_\ell)). \tag{19}$$

Recall that y_ℓ is the output gap in sector ℓ, and that output stability is determined by $\mathrm{E}[y_\ell^2]$, which aggregates the output gap across the economy. Taking appropriate expectations,

$$\mathrm{E}[y_\ell^2 | \theta] \propto \mathrm{E}[(\mathrm{E}[\theta | x_\ell] - P(x_\ell))^2 | \theta] \equiv L_Y. \tag{20}$$

Using (5) and Proposition 1, and following some algebraic manipulation, it is straightforward to show that the expectation L_Y is independent of θ and satisfies

$$L_Y = \frac{1}{\sum_{i=1}^{n} \psi_i} \left[\frac{\overline{\beta}}{\hat{\beta}} - 1 \right], \tag{21}$$

where $\hat{\beta}$ is the benchmark precision-weighted average publicity, and $\overline{\beta}$ is the equilibrium-weighted average publicity, and where $\hat{\beta} = \overline{\beta}$ if and only if $\beta_j = \beta_{j'}$ for all j and j'.

Note immediately that (21) must be weakly positive (since $\overline{\beta} \geq \hat{\beta}$). Output variation is eliminated (that is, $L_Y = 0$) if all signals share the same publicity or, equivalently, the same (conditional) correlation coefficient: if all information is identically correlated (or in effect, there is a single signal) then there are no output gaps.

Proposition 2. *The output gap is identically zero* (*and so output stability is maximized*) *when all signals share the same correlation coefficient* (*so that* $\rho_j = \rho_{j'}$ *for all* j *and* j').

Output gaps arise from the divergence of the price-setting process and the expectation-formation process. When there is one signal (or many identically correlated signals) this cannot happen. An immediate corollary arises: in the absence of any substantive prior and with a single signal or with multiple signals sharing the same correlation coefficient there is no role whatsoever for further announcements. That is, if a central bank (for example) provides an additional $(n+1)$th signal, because the output gap is identically zero to start with in these instances, things can only be made worse.

Corollary to Proposition 2. *When there is a single signal* (*or many identically correlated signals*) *public announcements can only reduce output stability*.

Nevertheless, announcements (that is, the release of additional informative signals) can be helpful when the conditions of Proposition 2 fail; that is, when islands receive multiple signals with different publicities or when there is a substantive prior. Such announcements are considered in subsequent sections of the paper.

A possible critique of Proposition 2 and its corollary is that the fundamental θ does not matter directly (demand depends only on expectations of θ) and so it is unsurprising that announcements are not always useful. If θ matters directly, so that demand is driven by a local shock $\theta_\ell \sim N(\theta, \nu^2)$, then a possible conjecture is that announcements are always valuable. This is not so: the spirit of the corollary to Proposition 2 remains. To see this, consider a world in which there are no information sources other than the local demand shock θ_ℓ. In this case, the solution reduces to $p_\ell = \theta_\ell$, which in turn eliminates the output gap in all islands; prices adjust one-for-one to nominal aggregate demand. Thus, the addition of any other informative signal can only worsen matters.

Criteria other than $\mathrm{E}[y_\ell^2] \propto L_Y$ could be used to measure macroeconomic performance; some are discussed in the online appendix. In the Lucas-Phelps setting, L_Y tracks real deviations in the economy, whereas other measures focus on nominal deviations. The nominal values of θ and of aggregate prices $\overline{p}$ do not in themselves matter for pricing decisions; it is precisely expectations of the fundamental and of the economy-wide price level that determine aggregate demand and supply respectively. Therefore, the deviation of prices from expectations is exactly what matters. Expectations of the fundamental are formed according to (5), for instance; prices are set using the weights described in Proposition 1. Only when these weights differ will there be any real-output implication. The expression in (21) accurately reflects the different weights that come into play for expectations formation and price-setting through its emphasis on the divergence between $\hat{\beta}$ and $\overline{\beta}$. When there is no divergence, there is no output variation.

3.3. Publicity and precision

An output-stabilizing planner considering whether to release an informative signal j might not reasonably be expected to manipulate ψ_j (precision) and β_j (publicity) directly; more sensible would be to consider the (partial) control of $1/\xi_j^2$ or $1/\kappa_j^2$. Under the interpretation of Section 2.2 the former can be seen as the clarity of an announcement, over which a planner might have some influence, whilst the latter is the precision with which the planner sees the fundamental. Of course ψ_j and β_j can be written in terms of ξ_j^2 and κ_j^2, yielding indirect control over the publicity and precision; but one cannot be changed without an impact upon the other. Nevertheless, a starting point for an analysis of output stability (using L_Y) is provided in Propositions 3 and 4.

Proposition 3. *Output stability is quasi-concave in each β_j: it is increasing for all $\beta_j < \overline{\beta}$ and decreasing for all $\beta_j > \overline{\beta}$. Hence stability is maximized by setting $\beta_j = \overline{\beta}$.*

Put succinctly, this says that stability is enhanced by "averagely public" signals; for instance, a planner would like to reduce the publicity of a relatively public signal. Informative signals with extreme publicity (whether extremely private or extremely public) drive a wedge between prices and expectations, so opening output gaps.

Proposition 4. *Fixing the publicity β_j of a signal, output stability is increasing in the signal's precision ψ_j if and only if its publicity is relatively average. More formally,*

$$\frac{\partial L_Y}{\partial \psi_j} < 0 \Leftrightarrow (\beta_j - \overline{\beta})^2 < \overline{\beta}^2 - \hat{\beta}^2. \tag{22}$$

Moreover, stability is quasi-convex in the signal's precision. Fixing the publicity, it is optimal to either (i) withhold a signal entirely or (ii) release it with as much precision as possible.

More information is good if and only if the signal's publicity is "relatively average" in the sense of Proposition 4; both "very public" and "very private" information can be harmful. It has been noted that signals with publicities that differ markedly from the average drive apart the expectations-formation and price-formation processes; as they become more precise (locally) the problem is exacerbated as they gain influence.

It is instructive to consider these insights in the context of a two-signal world with a purely public signal ($\rho_1 = 1$, so that $\beta_1 = 1/\pi$) and a purely private signal ($\rho_2 = 0$, so that $\beta_2 = 1$). This is the standard model found in the preceding literature; it also corresponds to a single perfectly private signal coupled with a substantive common prior. Clearly $\beta_1 > \overline{\beta} > \beta_2$. In such a world there is always a lower range of ψ_1 for which L_Y is increasing in ψ_1. Making purely public information more precise reduces output stability for this range. Confirming the Corollary to Proposition 2, stability is maximized by setting $\psi_1 = 0$, which is equivalent to releasing no information.

For ψ_1 sufficiently large, L_Y is decreasing in ψ_1 and so stability is improved locally by increasing the precision of the public signal. In this world $\partial L_Y / \partial \psi_1 < 0$ if and only if $\psi_1 > \psi^*$ where, by substituting in the expression in Proposition 4 for β_1 and β_2,

$$\psi^* \equiv \frac{\psi_2}{4}\left[\sqrt{1+8\pi} - 1\right]. \tag{23}$$

ψ^* is increasing in π and ψ_2. When π is higher the pricing rule places less weight on $E_\ell[\overline{p}]$ and so the price-formation process is less biased toward the public signal. As a result the public signal does not serve as an effective coordination device until its precision is higher: it is for these higher values of ψ_1 that more information is better (locally). ψ^* is also increasing in ψ_2. A similar intuition applies: the higher ψ_2 the higher the quality of the purely private signal, and the less relatively useful the purely public signal becomes.

However, since output gaps are eliminated when $L_Y = 0$, a zero-precision signal is better than $\psi_1 > 0$ no matter how large is ψ_1. Only if a "perfectly precise" public signal ($\sigma_1^2 = 0$) is available will it do as well as a zero-precision signal. This is because output gaps are the result of a divergence between price setting and expectations. If each island receives one signal only then this divergence cannot arise. It does not matter which signal is heard, just that a sector's price does not deviate from the perception of the price level; a deviation can happen only when more than one source of information receives attention. (Of course, the presence of a prior means that more than one source is typically present.)

Returning to the point made just prior to Proposition 3, the focus here is on a situation in which there is no strong distinction between public and private information. Rather, the publicity of a signal is indexed by $\beta_j \in [1, 1/\pi]$; and there are many such signals. Nevertheless a result analogous to the preceding discussion is a corollary of Proposition 4.

Corollary to Proposition 4. *For each signal, there exists ψ_j^* such that for all $\psi_j \geq \psi_j^*$ output stability is increasing in precision. If the signal is neither too public nor too private then $\psi_j^* = 0$.*

This reinforces a central message: there are differences in the publicities (equivalently, correlations) of signals that can separate price formation and expectations formation.

4. Communication design with commitment

This section studies the communication policy of an output-stabilizing central bank where credible and observable commitments to an information structure are possible.

4.1. Optimal announcements

If a planner (the central bank) has to decide whether to release information, it seems unlikely that it would have full control over the publicity and the precision of the signal. The approach favoured here is to allow limited control over ξ_j^2 and κ_j^2 for some information source j. This fits with the interpretation of these variances given in Section 2.2: the bank may manipulate the clarity with which the information is communicated and the precision with which it is observed.

From (8) and Proposition 1, ψ_j and β_j may be written

$$\psi_j = \frac{1}{\kappa_j^2+\xi_j^2} \quad \text{and} \quad \beta_j = \frac{\kappa_j^2+\xi_j^2}{\pi\kappa_j^2+\xi_j^2}. \tag{24}$$

Any change in ξ_j^2 (or in κ_j^2) changes both ψ_j and β_j. Improved clarity (ξ_j^2 falls) increases both precision and publicity, whereas improved quality (κ_j^2 falls) increases precision, but decreases publicity. It is possible to characterize the impact upon stability that a local change in any ξ_j^2 or κ_j^2 would have in terms of the publicity term β_j.

Proposition 5. *Fix $n \geq 2$ signals with clarities ξ_j^2 and qualities κ_j^2. For each signal j,*

$$\frac{\partial L_Y}{\partial \xi_j^2} > 0 \Leftrightarrow \beta_j \in (\beta_\xi, \beta^\xi) \quad \textit{and} \quad \frac{\partial L_Y}{\partial \kappa_j^2} > 0 \Leftrightarrow \beta_j \in (\beta_\kappa, \beta^\kappa), \tag{25}$$

where these intervals' boundaries satisfy: $\max\{1,\beta_\xi\} < \beta_\kappa < \overline{\beta} < \beta^\xi < \min\{1/\pi, \beta^\kappa\}$. *The four interval boundaries (β_ξ, β^ξ, β_κ, and β^κ) depend only on the two measures of average publicity*.

If a signal is neither too public nor too private (if $\beta_\kappa < \beta_j < \beta^\xi$) then output variation can be reduced (locally) by enhancing the signal's quality (a reduction in κ_j^2) or its clarity (a reduction in ξ_j^2). If the information source is sufficiently private or public, however, at least one claim will fail. For instance, if $\beta > \beta^\xi$ (a sufficiently public signal) then increasing ξ_j^2 is helpful, as it reduces the publicity of the signal. More generally, stability is helped (locally) by less clarity (or more "receiver noise") when an information source is very public, and by lower quality (or more "sender noise") when a source is very private.

Suppose that the central bank has at its disposal a signal with underlying quality $\tilde{\kappa}^2$ and clarity $\tilde{\xi}^2$. The bank may reduce the quality of the signal (it might credibly do so by removing research staff) communicate with less than maximal clarity (perhaps by obfuscatory announcements), but cannot improve the underlying quality and clarity so easily. This is represented by a choice of κ^2 and ξ^2 such that $\kappa^2 \geq \tilde{\kappa}^2$ and $\xi^2 \geq \tilde{\xi}^2$. Altering these parameters will impact both the signal's precision and its publicity. The lower bounds for clarity and quality, $\tilde{\xi}^2 \geq 0$ and $\tilde{\kappa}^2 \geq 0$ represent the "technology" available to the central bank, and it is assumed that $\max\{\tilde{\xi}^2, \tilde{\kappa}^2\} > 0$, so that the technology never admits a perfectly revealing signal. Hence the publicity of a bank's technology is

$$\tilde{\beta} = \frac{\tilde{\kappa}^2+\tilde{\xi}^2}{\pi\tilde{\kappa}^2+\tilde{\xi}^2}. \tag{26}$$

Notions of relative publicity for the bank's technology are straightforward. Beginning in a world without the bank, suppose that there are $n \geq 2$ distinct signals so that the equilibrium-weighted average publicity satisfies $\overline{\beta} \in (1, 1/\pi)$. The bank's technology is relatively public if $\tilde{\beta} > \overline{\beta}$ and relatively private if $\tilde{\beta} < \overline{\beta}$. In choosing the actual characteristics of any announcement made, the central bank degrades the signal's quality if $\kappa^2 > \tilde{\kappa}^2$, and degrades its clarity if $\xi^2 > \tilde{\xi}^2$. With this terminology in hand, Proposition 6 shows how these parameters ought to be chosen to maximize output stability.

Proposition 6. *Fix $n \geq 2$ distinct signals, so that $\overline{\beta} \in (1, 1/\pi)$. A central bank has an extra information source at its disposal, and chooses ξ^2 and κ^2 to maximize output stability*.

(i) *If the technology is relatively public then it maximizes its signal's quality; it degrades clarity if its technology is sufficiently public ($\tilde{\beta} > \beta^\xi$); its signal's publicity satisfies $\overline{\beta} \leq \beta \leq \max\{\beta^\xi, \tilde{\beta}\}$.*
(ii) *If the technology is relatively private then it maximizes its signal's clarity; it degrades quality if its technology is sufficiently private ($\tilde{\beta} < \beta_\kappa$); its signal's publicity satisfies $\min\{\beta_\kappa, \tilde{\beta}\} \leq \beta \leq \overline{\beta}$.*
(iii) *If the bank's technology is neither relatively public nor relatively private ($\tilde{\beta} = \overline{\beta}$), the optimal choice satisfies $\xi^2 = \tilde{\xi}^2$ and $\kappa^2 = \tilde{\kappa}^2$; its signal's publicity satisfies $\beta = \tilde{\beta} = \overline{\beta}$.*

A bank may wish to degrade its signal's quality or its clarity, but never both. The claims also imply that it never degrades a signal completely.[6] Next, consider a perfectly public signal technology. If $\tilde{\xi}^2 = 0$ then $\tilde{\beta} = 1/\pi$, and so case (i) applies; κ^2 is chosen as small as possible. Now note that $\tilde{\beta} > \beta^\xi$ since $\beta^\xi < 1/\pi$ (from Proposition 5). It follows, from Proposition 6, that

[6] In case (i) the central bank may choose to degrade its clarity. If it did so completely then the signal would become relatively private. However, the optimal clarity satisfies $\beta \geq \overline{\beta}$, and so the signal is only partially degraded, if at all. A similar argument applies to case (ii).

clarity will certainly be degraded. Finally, if the bank is able to identify perfectly the fundamental then case (ii) applies: it should communicate with maximal clarity, but should damage the signal's quality by choosing $\kappa^2 > 0$, since $\tilde{\beta} < \beta_\kappa$.

Corollary to Proposition 6. *So long as there are $n \geq 2$ existing signals with distinct correlations, a central bank would never wish to withhold its information completely. When it is possible to release a purely public signal, the bank never wishes to do so: it degrades the clarity of its communication. Similarly, if the bank can identify perfectly the underlying fundamental, it never wishes to do so: it degrades the quality of its information acquisition.*

Driving this corollary is the desire for averagely public information; this reduces the undesirable wedge between price formation and expectations formation.

4.2. Optimal obfuscation

This section considers the optimal obfuscation (equivalently, optimal clarity) of an output-stabilizing central bank when there are two existing information sources available to each island sector. The first is a purely public signal with precision $\psi_1 = 1-\omega$, and the second is a purely private signal with precision $\psi_2 = \omega$. The corresponding publicities of these signals are $\beta_1 = 1/\pi$ and $\beta_2 = 1$ respectively. The fact that $\psi_1 + \psi_2 = 1$ is a normalization which is made without the loss of any generality, and so, fixing the total amount of information available to an island, the parameter ω reflects the relative importance of purely private versus purely public information.

The model specification prescribes a diffuse (improper) prior over θ, and so any substantive prior beliefs held by the economy's inhabitants must be incorporated as one of the signals available to them. This means that $\psi_1 = 1-\omega$ can be interpreted as the precision of a common prior, and so $\psi_2 = \omega$ represents the relative precision of any new (private) information. Allowing ω to become small can be interpreted as a situation in which the identity of the economy's nominal anchor is well established, and allowing ω to become large reflects a situation in which islands are readily influenced by new information.

A central bank has at its disposal a third information source (suppressing subscripts) which it may release (if it wishes) with perfect clarity ($\tilde{\xi}^2 = 0$) but which imperfectly reveals the fundamental ($\tilde{\kappa}^2 > 0$). The precision of the bank's information is $\tilde{\psi} \equiv 1/\tilde{\kappa}^2$, which in turn represents (given the normalization $\psi_1 + \psi_2 = 1$) the precision of its information relative to the precision of the interim beliefs held on an island.

With these parameter values Proposition 6 reveals that a central bank always chooses $\kappa^2 = \tilde{\kappa}^2$ and an optimal (and obfuscatory) $\xi^2 > 0$, or equivalently an optimal publicity satisfying $1 < \beta < \tilde{\beta} = 1/\pi$. The precision and correlation of the released signal are

$$\psi = \frac{1}{\tilde{\kappa}^2 + \xi^2} \quad \text{and} \quad \rho = \frac{\tilde{\kappa}^2}{\tilde{\kappa}^2 + \xi^2} = \frac{\psi}{\tilde{\psi}}. \tag{27}$$

Hence ρ is the precision of the released signal relative to the quality of the information on which it is based; equivalently, it captures the transparency of the bank's announcement. When $\rho = 1$ the bank openly releases its information and so generates a perfectly public signal, whereas it can only achieve a perfectly private signal satisfying $\rho = 0$ by babbling (allowing $\xi^2 \to \infty$) and so (effectively) throwing its information away.

Summarizing, the exogenous parameters for the comparative-static exercises which follow are ω (the importance of private signals relative to the prior), π (the responsiveness of aggregate demand relative to aggregate supply), and $\tilde{\psi}$ (the precision of the central bank's information source relative to agents' interim beliefs). Fig. 1 plots the optimal transparency against ω and π for two different values of $\tilde{\psi}$.

When private signals are swamped by prior beliefs (corresponding to $\omega \approx 0$) the average publicity of the information available to the agents is very high (close to $1/\pi$). In order to release "averagely public" information, the bank releases its signal transparently, so that $\rho \approx 1$. As the relative importance of prior beliefs fall, so that the nominal anchor is highly uncertain ex ante, the central bank responds by obfuscating; it becomes less transparent in communicating its own information about the fundamental.

The signal's quality is always degraded ($\psi < \tilde{\psi}$): its clarity is imperfect. However (compare Fig. 1a and b), if the bank's own information improves it also enhances its transparency: a bank with relatively good information ought to speak relatively clearly.

Finally, consider the changes in the optimally chosen ρ with respect to π. As π increases, the clarity with which the central bank ought to release its information falls. For higher values of ω, where the purely private signal is very precise relative to the prior, ρ falls very rapidly indeed as π increases. It is here that, to a great extent, the private signal drowns out the prior in the equilibrium price-setting weights. Any very public signal released by the bank would inevitably drive a wedge between the price-formation process and the expectations-formation process. To avoid doing so, the bank must obscure its message and release an uncorrelated and relatively uninformative signal. For low values of π when the prior is relatively strong, the bank releases a correlated and very public signal to reinforce the already strong connection between expectations and price setting.

5. Costly information acquisition and transmission

Section 4 focuses on an output-stabilizing central bank that is able to influence (albeit indirectly) the weights placed on the signals in the equilibrium pricing rule. It is via this mechanism that the benefits of reducing the quality or clarity of a

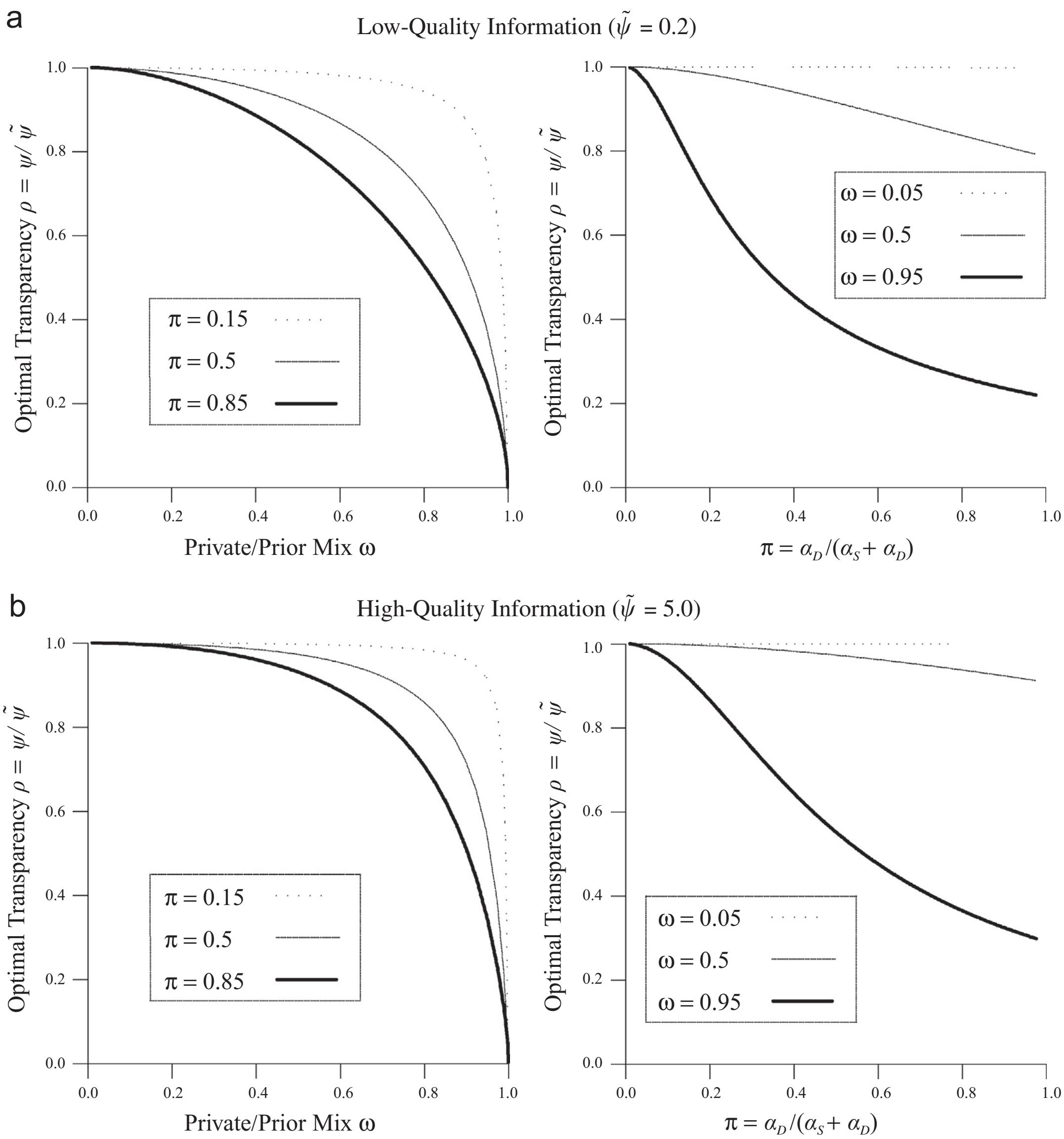

Fig. 1. Optimal transparency for a central bank announcement. These figures report optimal transparency when the central bank's underlying signal has precision $\tilde{\psi}$. When communication noise is added, the precision of its announcement is reduced to $\psi < \tilde{\psi}$. $\rho = \psi/\tilde{\psi}$ measures the bank's transparency. The parameter ω is the islands' existing mix of private and public information.

particular signal arise. In the absence of such influence there is no benefit to be gained by obfuscation and the bank would prefer strictly to improve the precision of any given signal.

Allowing the central bank to influence the weights in such a way is a reasonable modelling choice in circumstances in which the bank can make credible, irreversible, and observable pre-commitments to alter the quality and clarity of its information. In other situations it may be better to model the bank's clarity and quality choices as simultaneously chosen with the weights. Given the argument above, the bank now has a strict incentive to improve the accuracy and transparency of its information source. Nevertheless, it is reasonable to imagine that there would be some cost of doing so.

In this section therefore, attention turns to a central bank which, simultaneously with the choice of weights in the pricing rules, picks the quality $(1/\kappa^2)$ and clarity $(1/\xi^2)$ of a particular signal j at its disposal. The other $i \neq j$ signals have fixed values of κ_i^2 and ξ_i^2 beyond the bank's control. The cost of manipulating signal j's quality and clarity is

$$C\left(\frac{c_\kappa}{\kappa^2} + \frac{c_\xi}{\xi^2}\right) \quad \text{where } \sqrt{c_\kappa} + \sqrt{c_\xi} = 1 \tag{28}$$

is a harmless normalization, and where $C'(\cdot)>0$. The pricing rules operate as before: the anticipated characteristics of signal are written $1/\kappa_j^2$ and $1/\xi_j^2$. The market-clearing prices must correctly anticipate the bank's choice, so $\kappa_i^2=\kappa^2$ and $\xi_i^2=\xi^2$ in equilibrium.

The objective is now to minimize the sum of the measure of output variation L_Y and its costs $C(\cdot)$. L_Y is defined in (20). From (5), $\mathrm{E}[\theta|x_\ell]=\sum_{i=1}^n \overline{w}_i x_{i\ell}$, where $\overline{w}_i \propto \psi_i$, so incorporating the equilibrium pricing rule found in Proposition 1,

$$\mathrm{E}[\theta|x_\ell]-P(x_\ell)=\sum_{i=1}^n(\overline{w}_i-w_i)x_{i\ell}=\sum_{i=1}^n(\overline{w}_i-w_i)(x_{i\ell}-\theta). \tag{29}$$

Finally, squaring and taking expectations to recover an alternative formulation for L_Y,

$$L_Y=\sum_{i=1}^n(\overline{w}_i-w_i)^2\mathrm{var}[x_{i\ell}|\theta]=(\overline{w}_j-w_j)^2(\kappa^2+\xi^2)+\sum_{i\neq j}(\overline{w}_i-w_i)^2(\kappa_i^2+\xi_i^2). \tag{30}$$

The weights w_j are the equilibrium weights presented in Proposition 1; the weights $\overline{w_j}$ similarly depend upon the anticipated values of the quality and clarity parameters across the set of information sources. The bank simultaneously chooses κ^2 and ξ^2, the variance terms of the jth signal. The latter terms of (30) are exogenous from the bank's perspective, whose problem (to minimize L_Y+C) therefore may be reduced to

$$\min_{\kappa^2,\xi^2}\left\{(\overline{w}_j-w_j)^2(\kappa^2+\xi^2)+C\left(\frac{c_\kappa}{\kappa^2}+\frac{c_\xi}{\xi^2}\right)\right\}. \tag{31}$$

There is an incentive to engage in costly information acquisition or transmission if and only if $w_j\neq\overline{w}_j$. Note that $\psi_j=0$ is a sufficient condition for $w_j=\overline{w}_j$. Thus if the bank's information is anticipated to be worthless, there is no incentive for the bank to acquire (or release) any costly information, and indeed the “information” is worthless as anticipated. There will always be an equilibrium of this form so long as $\psi_j=0$ is admitted. Of course, the presence of any unpreventable yet small amount of information issuing from the planner (restricting $\psi_j\geq\varepsilon>0$ for instance) may rule out such an equilibrium, and it is in this spirit that the remainder of the section proceeds.

If $\psi_j>0$ it may still be the case that the bank has no incentive to obtain and transmit costly information. In particular, and using the definition in (18), if $\psi_j>0$,

$$w_j=\overline{w}_j \Leftrightarrow \frac{\beta_j\psi_j}{\sum_{i=1}^n\beta_i\psi_i}=\frac{\psi_j}{\sum_{i=1}^n\psi_i}\Leftrightarrow\beta_j=\frac{\sum_{i=1}^n\beta_i\psi_i}{\sum_{i=1}^n\psi_i}\equiv\hat{\beta}. \tag{32}$$

If the information source j is averagely public (in the sense of the precision-weighted average) then the bank has no incentive to acquire or transmit this information. When $w_j\neq\overline{w}_j$, then the very first term in the bank's minimization problem is

$$(w_j-\overline{w}_j)^2=\left[\frac{\psi_j(\beta_j-\hat{\beta})}{\sum_{i=1}^n\beta_i\psi_i}\right]^2. \tag{33}$$

In other words, the incentive to acquire and transmit information is strongest whenever information source j is very far from publicly average (when β_j is very different from $\hat{\beta}$) and when ψ_j is very different from zero. Note, however, that if (fixing everything else) $\psi_j\to\infty$ then $\beta_j\to\hat{\beta}$. If the signal is extremely precise it receives almost all weight in the pricing rule, and so it is by definition averagely public (it is virtually the only signal used). Proposition 7 collects together these observations.

Proposition 7. *The central bank's incentives to acquire and transmit signal j are greatest when its anticipated precision takes an intermediate value, $\psi_j\in(0,\infty)$, and they increase as its anticipated publicity β_j diverges from precision-weighted average publicity $\hat{\beta}$.*

Recall the message of Section 3.3, and in particular that of Proposition 3: if a central bank has control over an information source's publicity, output stability is maximized when it is set to be averagely public (in the sense of equilibrium-weighted average publicity $\overline{\beta}$). However, when the signal at the bank's disposal is anticipated to be averagely public (in the sense of precision-weighted average publicity $\hat{\beta}$), there is no incentive to acquire or transmit that information when it is costly to do so. This is natural: the larger the difference between signal j's publicity and average publicity, the more it contributes to driving apart the price-setting and expectations-formation processes. By acquiring and transmitting more information about this signal, the bank must surely increase its precision ψ_j, driving its publicity closer to the average. As this convergence occurs, the incentive to engage further in information acquisition is necessarily reduced.

Corollary to Propositions 3 and 7. *A central bank would like signal j to be averagely public* (*Proposition* 3). *However*, *when the bank's signal is anticipated to be averagely public, so that $\beta_j=\hat{\beta}$, there is no incentive to acquire or transmit that information* (*Proposition* 7).

Returning to the loss function in (31), consider the marginal rate of substitution and marginal rate of transformation between signal quality and signal clarity:

$$\mathrm{MRS} = \frac{\partial L_Y/\partial\kappa^2}{\partial L_Y/\partial\xi^2} = 1 \quad \text{and} \quad \mathrm{MRT} = \frac{\partial C/\partial\kappa^2}{\partial C/\partial\xi^2} = \frac{c_\kappa/(\kappa^2)^2}{c_\xi/(\xi^2)^2}. \tag{34}$$

Equating these two objects yields $\kappa^2/\xi^2 = \sqrt{c_\kappa/c_\xi}$. Fixing the total cost of information acquisition and transmission, the optimal ratio of quality to clarity depends only upon their relative costliness. This means that for any equilibrium with positive acquisition and transmission, and regardless of the form that $C(\cdot)$ takes, the optimal correlation coefficient and publicity for the information source at the bank's disposal are given by

$$\rho = \frac{\kappa^2}{\kappa^2+\xi^2} = \frac{\sqrt{c_\kappa}}{\sqrt{c_\kappa}+\sqrt{c_\xi}} = \sqrt{c_\kappa} \quad \text{and} \quad \beta = \frac{1}{1-(1-\pi)\rho} = \frac{1}{\pi\sqrt{c_\kappa}+\sqrt{c_\xi}}. \tag{35}$$

In equilibrium, the publicity of j is correctly anticipated, so $\beta_j = \beta$. To calculate the optimal precision ψ with which the bank releases signal j note first that $\rho = \psi\kappa^2$ and $1-\rho = \psi\xi^2$, therefore

$$C\left(\frac{c_\kappa}{\kappa^2} + \frac{c_\xi}{\xi^2}\right) = C\left(\frac{\psi c_\kappa}{\rho} + \frac{\psi c_\xi}{1-\rho}\right) = C\left(\psi\left(\sqrt{c_\kappa}+\sqrt{c_\xi}\right)\right) = C(\psi). \tag{36}$$

Thus the problem may be written $\min_\psi\{(\overline{w}_j - w_j)^2/\psi + C(\psi)\}$. At an interior solution for ψ, the optimal level of precision solves $\psi\sqrt{C'(\psi)} = |\overline{w}_j - w_j|$.

The discussion so far places no restrictions on $C(\cdot)$. If costs are linearly related to the sample sizes of (for example) research activities, then such costs will be linear in the precisions $1/\kappa^2$ and $1/\xi^2$. The associated specification $C(x) = cx$ also permits sharper results.

If $C(x) = cx$ then the precision choice becomes $\psi = |\overline{w}_j - w_j|/\sqrt{c}$. Optimal precision is increasing in the gap between the weight attached to signal j in the expectations-formation process and the weight attached to the signal in the price-setting process.

Define $\hat{\beta}_{-j}$ to be the (precision-weighted) average publicity of all the signals excluding j, and define $\hat{\psi}_{-j}$ to be the total precision of those $n-1$ signals:

$$\hat{\beta}_{-j} \equiv \frac{\sum_{i\neq j}\psi_i\beta_i}{\sum_{i\neq j}\psi_i} \quad \text{and} \quad \hat{\psi}_{-j} \equiv \sum_{i\neq j}\psi_i. \tag{37}$$

Using this notation, the problem in (31) is solved by

$$\psi = \frac{1}{\sqrt{c}}\left|\frac{\psi_j}{\psi_j+\hat{\psi}_{-j}} - \frac{\psi_j\beta_j}{\psi_j\beta_j+\hat{\psi}_{-j}\hat{\beta}_{-j}}\right| \quad \text{and} \quad \beta = \frac{1}{\pi\sqrt{c_\kappa}+\sqrt{c_\xi}}. \tag{38}$$

In equilibrium the bank's choices are correctly anticipated: $\beta = \beta_j$ and $\psi = \psi_j$. This means that the first equality in (38) can be solved explicitly for ψ. Clearly $\psi = 0$ always yields a solution. Suppose on the contrary $\psi > 0$. Then ψ can be cancelled leaving a quadratic in ψ. The roots are real so long as $c < c^*$ where $c^* \equiv [(\beta - \hat{\beta}_{-j})/\hat{\beta}_{-j}\hat{\psi}_{-j}]^2$. Whenever costs are small enough, there is an equilibrium where the central bank obtains and transmits information about source j.

Proposition 8. *Suppose that information acquisition costs are linear*: $C(x) = cx$. *Then there exists* $c^* > 0$ *such that if* $c > c^*$ *the central bank is ignored and engages in no information acquisition or communication in the unique equilibrium. If* $c < c^*$ *the bank provides a costly and informative signal j whose equilibrium precision and publicity solve* (38) *with* $\psi = \psi_j > 0$ *and* $\beta = \beta_j$.[7]

The messages from this proposition also apply when $C(\cdot)$ is non-linear. For example, if $C'(x) > c^*$ for all x then there is a unique equilibrium where the central bank is ignored; similarly, if $C'(x) < c^*$ for all x then in equilibrium the bank provides costly information. The former case is likely to apply when there are decreasing returns to research activities so that $C(\cdot)$ is convex; the relevant condition becomes $C'(0) > c^*$. However, a concave specification for $C(\cdot)$ may also be appropriate. Information processing costs are naturally concave in signal precisions when they emerge from a rational inattention specification (Sims, 2003, 2011; Maćkowiak and Wiederholt, 2009). Indeed, in such cases the increasing returns can generate multiple equilibria; Section 8 of Myatt and Wallace (2012) reports an example. Nevertheless, for this case $C'(0) < c^*$ is sufficient to guarantee a central bank's participation in the information provision process.

To explore the consequences of this proposition, consider the special case when the signals available to the islands consist of one perfectly public information source (j) and one (or many) perfectly private information sources. This is the standard framework in much of the literature. Suppose that the central bank can manipulate the perfectly public information source, and that $c_\xi = 0$ (so that, by the normalization, $c_\kappa = 1$). Then, by Proposition 8, with reference to (38),

[7] Technically, there is an equilibrium with $\psi = 0$. If $\psi \geq \varepsilon > 0$ is imposed then $\psi = \varepsilon$ is only an equilibrium when $c > c^*$. That is, if $c < c^*$ then $\psi = \varepsilon$ is not an equilibrium for small enough $\varepsilon > 0$.

optimal publicity is $\beta = 1/\pi$. Now $\hat{\beta}_{-j} = 1$ in this instance: (all the) perfectly private signals $i \neq j$ have $\beta_i = 1$. Thus

$$c^* \equiv \left[\frac{\beta - \hat{\beta}_{-j}}{\hat{\beta}_{-j}\hat{\psi}_{-j}}\right]^2 = \left[\frac{\beta - 1}{\hat{\psi}_{-j}}\right]^2 = \left[\frac{1-\pi}{\pi\hat{\psi}_{-j}}\right]^2 > 0. \tag{39}$$

Now in this environment, as Corollary to Proposition 2 confirms, setting $\psi = 0$ (or equivalently, not releasing a signal at all) ensures the output gap is identically zero: the first best is achieved. This is indeed the equilibrium so long as $c > c^*$. However, whenever $c < c^*$ the equilibrium described in Proposition 8 involves $\psi > 0$, leading to costly information acquisition and positive variation in the output gap.

Corollary to Propositions 2 and 8. *Lowering the cost of information acquisition and transmission can widen the output gap and, as a consequence, make the central bank worse off.*

Lower costs of acquisition raise the information provision anticipated by the islands; the resultant increased spread in publicity drives a wedge between prices and expectations, and so generates an output gap; this provides the central bank with a self-fulfilling incentive to provide new information and bear a further cost. Clearly, in this case, the bank would prefer to be able to commit to provide no new information at all.

6. Related literature and concluding remarks

Morris and Shin (2002) studied a quadratic-payoff coordination game in the spirit of the classic Keynes (1936, Chapter 12) beauty-contest parable. They found that higher-order beliefs lead players to abandon highly informative (but not commonly known) private signals in favour of focal public ones. Their equilibrium is closely related to the equilibrium prices in an island economy (Phelps, 1969, 1970, 1983; Lucas, 1972, 1973; Amato et al., 2002). Morris and Shin (2005) emphasized that "[w]hen there is the potential for a strong consensus […] incentives may become distorted in such a way as to reduce the informational value of economic outcomes." They used a nominal performance criterion; specifically, the deviation of nominal prices from a nominal anchor.

Woodford (2005) and others have recognized that a real measure may be more appropriate. For example, Angeletos and Pavan (2004, 2007) considered an investment game for which welfare is the sum of players' payoffs. Hellwig (2005) followed in the spirit of earlier literature (Blanchard and Kiyotaki, 1987; Kiyotaki, 1988; Woodford, 2003) by studying the incomplete nominal adjustment of monopolistic firms, and here price dispersion drives welfare effects; the comparative-static exercises differ markedly from those of Morris and Shin (2002, 2005). In a recent contribution to this literature, Llosa and Venkateswaran (2013) allowed the firms to choose the precision of a purely private signal, much in the spirit of Myatt and Wallace (2012).

Most of the literature has focused on a two-signal public-and-private information structure. There have been some steps away from this: one such step appears in the supplementary material to Morris and Shin (2002), Angeletos and Pavan (2009) and Baeriswyl (2011) specified frameworks in which different players' private signal realizations are partially correlated; and Baeriswyl and Cornand (2011, 2007) considered a multiple-fundamental specification. More recently, models have emerged in which agents receive many informative signals: papers by Dewan and Myatt (2008, 2012), Hellwig and Veldkamp (2009), and Myatt and Wallace (2012) all allowed for this.

Relative to the literature, this article sharply focuses on the island-economy interpretation of the beauty contest model, derives its performance measure from the output gap, and exploits a richer information structure. This structure allows for many signals with arbitrary conditional correlation coefficients, and moves away from the public-and-private taxonomy: instead, a signal is characterized by its quality and its clarity. The literature has considered changes in the precisions of public and private signals. These amount to changes in a signal's quality and clarity respectively. The model here allows a signal to possess both properties, and leads naturally to the consideration of a signal's publicity. It is the difference in the publicity of signals, and not the presence of a perfectly public signal per se, which undesirably separates the price-setting and expectation-formation processes.

The results also provide a reassessment of the transparency of public announcements. The insight is that output gaps are closed by averagely public signals. A relatively public signal becomes more average by muddying its clarity, whereas a relatively private signal becomes more average by worsening its underlying quality. Contrary to Morris and Shin (2002), it is never optimal to release a purely public or a purely private signal; moreover, it is never optimal to withhold the signal completely. This implies that partial transparency, via obfuscatory communication, is a feature of optimal announcements. This resonates with the conclusions of Cornand and Heinemann (2008) who argued that the partial disclosure of a public signal is better than reducing the precision of a fully disclosed signal; this article and theirs offer complementary notions of partial publicity.

Of course, the incentive to engage in obfuscation or to damage information in other ways disappears if the bank (or other policy-maker) makes its acquisition and transmission decisions in private. The rationale for such behaviour is to influence the pricing rules used by the islands; an influence which is present only if the bank can commit to obfuscation both credibly and publicly. Modelling (costly) information provision as jointly endogenous with the pricing rules of the islands, the policy-maker's preference for averagely public signals remains: however, it is precisely such signals which minimize information-provision incentives in the first place. In fact, the incentive to engage in costly provision is greatest not for the most influential signals, but rather for those which deviate most from average publicity. Nevertheless, complementarities between quality (or clarity) choice and a signal's influence can lead to equilibria in which a policy-maker acquires and transmits information, even when it would be socially optimal to say nothing at all.

7. Proofs of Propositions 1–4

Proof of Proposition 1. The programming problem may be solved using traditional methods, resulting in first-order conditions of the form $2w_j(\pi\kappa_j^2+\xi_j^2)=\lambda+\mu_j$, where λ is the Lagrange multiplier on the constraint in (15) and μ_j is the multiplier on the implicit non-negativity constraint for w_j. Since $\sum_{i=1}^n w_i=1$, there is at least one j such that $w_j>0$. For this j, $\mu_j=0$ by complementary slackness, and hence $\lambda>0$. But then, by non-negativity of μ_j, $w_j>0$ for all j. Thus

$$w_j=\text{const}\times\frac{1}{\pi\kappa_j^2+\xi_j^2}\quad\text{where const}=1\Bigg/\sum_{i=1}^n\frac{1}{\pi\kappa_i^2+\xi_i^2},\tag{40}$$

so that the w_j's sum to one. Rewriting in terms of β_j as defined in the text and $\psi_j\equiv 1/\sigma_j^2$ leads to the first expression. The remainder of the proposition follows by inspection. □

Proof of Proposition 2. Follows by inspection of (21) (as does the corollary). □

Proof of Proposition 3. First-order conditions may be obtained from (21):

$$\frac{\partial L_Y}{\partial\beta_j}=\frac{1}{\hat\beta\sum_{i=1}^n\psi_i}\left[\frac{\partial\overline\beta}{\partial\beta_j}-\frac{\overline\beta}{\hat\beta}\frac{\partial\hat\beta}{\partial\beta_j}\right].\tag{41}$$

Differentiating $\overline\beta$ with respect to β_j yields

$$\frac{\partial\overline\beta}{\partial\beta_j}=\frac{\partial}{\partial\beta_j}\left[\frac{\sum_{i=1}^n\psi_i\beta_i^2}{\sum_{i=1}^n\psi_i\beta_i}\right]=\frac{2\beta_j\psi_j}{\sum_{i=1}^n\psi_i\beta_i}-\frac{\sum_{i=1}^n\psi_i\beta_i^2}{(\sum_{i=1}^n\psi_i\beta_i)^2}\psi_j=\frac{\psi_j}{\hat\beta\sum_{i=1}^n\psi_i}\left[2\beta_j-\overline\beta\right].\tag{42}$$

$\partial\hat\beta/\partial\beta_j=\psi_j/\sum_{i=1}^n\psi_i$. Hence, substituting back into the original expression gives

$$\frac{\partial L_Y}{\partial\beta_j}=\frac{2\psi_j}{(\hat\beta\sum_{i=1}^n\psi_i)^2}(\beta_j-\overline\beta).\tag{43}$$

This is zero, and hence there is a stationary point, at $\beta_j=\overline\beta$. It is positive for all $\beta_j>\overline\beta$ and negative for all $\beta_j<\overline\beta$. The function is therefore quasi-convex and has a unique minimum. □

Proof of Proposition 4. First, partially differentiate L_Y with respect to ψ_j:

$$\frac{\partial L_Y}{\partial\psi_j}=\frac{-1}{(\sum_{i=1}^n\psi_i)^2}\left[\frac{\overline\beta}{\hat\beta}-1\right]+\frac{1}{\hat\beta\sum_{i=1}^n\psi_i}\frac{\partial\overline\beta}{\partial\psi_j}-\frac{\overline\beta}{\hat\beta^2\sum_{i=1}^n\psi_i}\frac{\partial\hat\beta}{\partial\psi_j},\tag{44}$$

where $\partial\overline\beta/\partial\psi_j=\beta_j(\beta_j-\overline\beta)/\sum_{i=1}^n\psi_i\beta_i$ and $\partial\hat\beta/\partial\psi_j=(\beta_j-\hat\beta)/\sum_{i=1}^n\psi_i$, so

$$\begin{aligned}\frac{\partial L_Y}{\partial\psi_j}&=\frac{1}{(\sum_{i=1}^n\psi_i)^2}\left[\frac{\hat\beta-\overline\beta}{\hat\beta}+\frac{\sum_{i=1}^n\psi_i}{\hat\beta}\frac{\beta_j(\beta_j-\overline\beta)}{\sum_{i=1}^n\psi_i\beta_i}-\frac{\overline\beta\sum_{i=1}^n\psi_i}{\hat\beta^2}\frac{(\beta_j-\hat\beta)}{\sum_{i=1}^n\psi_i}\right]\\&=\frac{1}{(\hat\beta\sum_{i=1}^n\psi_i)^2}\left[\hat\beta(\hat\beta-\overline\beta)+\beta_j(\beta_j-\overline\beta)-\overline\beta(\beta_j-\hat\beta)\right]\\&=\frac{1}{(\hat\beta\sum_{i=1}^n\psi_i)^2}\left[\hat\beta^2+\beta_j(\beta_j-2\overline\beta)\right]=\frac{1}{(\hat\beta\sum_{i=1}^n\psi_i)^2}\left[(\beta_j-\overline\beta)^2-(\overline\beta^2-\hat\beta^2)\right].\end{aligned}\tag{45}$$

Hence $\partial L_Y/\partial\psi_j<0$ if and only if the second term in the above expression is negative, as required. To establish the quasi-concavity of L_Y, partially differentiate L_Y again and evaluate at a stationary point (where $\partial L_Y/\partial\psi_j=0$). First note that from the penultimate expression above:

$$\left.\frac{\partial^2L_Y}{\partial\psi_j^2}\right|_{\partial L_Y/\partial\psi_j=0}=\frac{1}{(\hat\beta\sum_{i=1}^n\psi_i)^2}\left[\hat\beta\frac{\partial\overline\beta}{\partial\psi_j}-\beta_j\frac{\partial\hat\beta}{\partial\psi_j}\right].\tag{46}$$

The sign of this second differential is therefore determined by the second term of this expression.

$$\left.\frac{\partial^2L_Y}{\partial\psi_j^2}\right|_{\partial L_Y/\partial\psi_j=0}<0\Leftrightarrow\frac{\hat\beta(\beta_j-\hat\beta)}{\sum_{i=1}^n\psi_i}-\frac{\beta_j^2(\beta_j-\overline\beta)}{\sum_{i=1}^n\psi_i\beta_i}<0\tag{47}$$

$$\Leftrightarrow\hat\beta^2(\beta_j-\hat\beta)-\beta_j^2(\beta_j-\overline\beta)<0.\tag{48}$$

Using the first-order condition $\hat{\beta}^2 = -\beta_j(\beta_j - 2\overline{\beta})$ from above and dividing by β_j,

$$\frac{\partial^2 L_Y}{\partial \psi_j^2}\Big|_{\partial L_Y/\partial \psi_j = 0} < 0 \Leftrightarrow (2\overline{\beta} - \beta_j)\left(\beta_j - \hat{\beta}\right) - \beta_j(\beta_j - \overline{\beta}) < 0$$
$$\Leftrightarrow [\overline{\beta} \mp \sqrt{\overline{\beta}^2 - \hat{\beta}^2}][\overline{\beta} \pm \sqrt{\overline{\beta}^2 - \hat{\beta}^2} - \hat{\beta}] \mp [\overline{\beta} \pm \sqrt{\overline{\beta}^2 - \hat{\beta}^2}]\sqrt{\overline{\beta}^2 - \hat{\beta}^2} < 0, \tag{49}$$

where the second line follows from the first-order condition substitution $\beta_j = \overline{\beta} \pm \sqrt{\overline{\beta}^2 - \hat{\beta}^2}$. The final inequality is equivalent to $(2\hat{\beta} + \overline{\beta})^2 > \overline{\beta}^2 - \hat{\beta}^2$, which holds since $\overline{\beta} \geq \hat{\beta} \geq 1$. Thus L_Y is quasi-concave in ψ_j. The remaining statement and the corollary follow from quasi-concavity. □

Acknowledgements

The authors thank colleagues, reviewers, the editors (Ricardo Reis and Klaus Adam), and seminar participants for valuable feedback; they also thank Abhinay Muthoo for his kind hospitality at Warwick which enabled the completion of the paper. Supplemental results and proofs omitted from the main paper are available as an online appendix via the journal's website.

Appendix A. Supplementary proofs and results

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jmoneco.2014.01.003.

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