When Transparency Improves, Must Prices Reflect Fundamentals Better?

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No. In the presence of speculative opportunities, investors can learn about both asset fundamentals and the beliefs of other traders. We show that this learning exhibits complementarity: learning more along one dimension increases the value of learning about the other. As a result, regulatory changes may be counterproductive. First, increasing transparency (i.e., making fundamental information cheaper to acquire) can make prices less informative when investors respond by learning relatively more about others. Second, public disclosures discourage private learning about fundamentals, while encouraging information acquisition about others. Accordingly, disclosing more fundamental information can decrease overall informational efficiency by decreasing price informativeness. (*JEL* G14, D82, G18)

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> If I may be allowed to appropriate the term speculation for the activity of forecasting the psychology of the market, and the term enterprise for the activity of forecasting the prospective yield of assets over their whole life, it is by no means always the case

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> that speculation predominates over enterprise. As the organization of investment markets improves, the risk of the predominance of speculation does, however, increase.[1]
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> —J. M. Keynes, *The General Theory of Employment, Interest and Money*

Financial regulations often change the information environment in an effort to reduce market uncertainty. Many policies improve transparency by decreasing the cost to investors of acquiring fundamental information (e.g., by mandating standardized reporting). Regulators also choose to directly disclose relevant public information to investors (e.g., through forward guidance). Our insight is to recognize that when evaluating the impact of such policies, it is critical to understand what information investors choose to acquire and why. As emphasized by the above quote, investors are driven not just by fundamentals, but also by speculative motives. We show that when investors have an incentive to learn about both asset fundamentals and the beliefs of others, prices can reflect both types of information. When speculative motives dominate, we find that improving access to information about asset fundamentals can be counterproductive.

We study the optimal information acquisition decision of investors who can choose how much to learn about fundamentals and the beliefs of others. We show that learning exhibits complementarity: learning more along one dimension increases the marginal value of learning along the other. Because of this complementarity, regulatory changes can exacerbate the very problems they are intended to address. First, we show that an increase in transparency can make prices less informative about fundamentals. Second, we find that greater public disclosure can both crowd out private learning about fundamentals as well as encourage more learning about other investors. As a result, the informational efficiency of publicly available information can decrease in response to such disclosures.[2]

Public announcements, such as earnings statements, provide a natural setting in which to study the trade-off between learning along these two dimensions. On the one hand, such announcements are an important, direct source of public information about an asset's fundamental value (e.g., firm cash flows and growth prospects). On the other hand, substantial evidence suggests investors disagree on the interpretation of such announcements (e.g., Kandel and Pearson 1995), which gives rise to speculative opportunities. We develop a stylized model in which long-lived (L) investors anticipate trading a risky asset with short-lived (S) investors, with whom they may disagree about the interpretation of an

[1] The epigraph to this article is drawn from *The General Theory of Employment, Interest and Money* by J.M. Keynes.

[2] Our measure of informational efficiency depends on the conditional variance of the asset's payoff, given any public disclosure and the asset price.

upcoming public announcement. The long-lived investors trade the asset pre- and post- announcement, and can choose how much information to acquire about both the asset's fundamentals and the beliefs of S investors.

We show that learning along these two dimensions exhibits complementarity: each investor finds learning about S investors' beliefs more valuable when she also learns more about asset fundamentals. The complementarity arises because the future payoff depends on a nonlinear combination of fundamental information and beliefs about the behavior of other investors. Specifically, the post-announcement price is a weighted average of L and S investors' valuation of the asset, conditional on the public announcement. As a result, the speculative benefit of being able to better predict the public announcement is amplified by knowing how S investors will react to it.

Importantly, our notion of complementarity differs from the concept of strategic complementarity that is frequently discussed in the literature. As we will detail in the next section, many existing papers focus on strategic complementarity *across* investors, that is, when it is more valuable for an investor to learn along a particular dimension (e.g., fundamentals) when other investors are also learning about the same. In contrast, we study a setting in which, for *each* investor, learning about one dimension (e.g., the beliefs of S investors) is more valuable when she learns more about another (e.g., fundamentals).[3] As such, our analysis highlights a novel channel through which financial market policies can affect investor decisions.

Specifically, complementarity in learning implies that regulatory changes in the information environment can have counterintuitive consequences. A number of financial regulations target transparency by reducing the costs of acquiring information about fundamentals. For instance, the events of the subprime crisis led to the introduction of higher requirements for the reporting loan-level data, as part of the Dodd-Frank Act (2010).[4] Similarly, the Sarbanes-Oxley Act (2002), which encourages greater standardization within the financial statements of publicly-traded firms, was passed in part as a response to the accounting scandals of the early 2000s (e.g., Enron, WorldCom, and Tyco). Finally, as noted by Dugast and Foucault (2017), in 2009 the SEC "mandated that financial statements be filed with a new language ... on the ground that it would lower the cost of accessing data for smaller investors."[5] While such

[3] Learning along these two dimensions are Edgeworth complements in our setting (see Milgrom and Roberts 1995 for more discussion). In our model, since L investors exhibit differences of opinions, there are no strategic considerations for learning (i.e., each L investor's information choice is unaffected by the behavior of other L investors).

[4] Prior to the financial crisis, issuers of MBS were only required to provide aggregate data, such as the weighted-average coupon, or distributional data, including the number of borrowers with a FICO score in a given range. In response, Congress passed Title IX of the Dodd-Frank Act (2010), which requires issuers of asset-backed securities to disclose mortgage-level data. While such data was available before, it was generally more difficult and expensive to access.

[5] See the SEC Ruling on Interactive Data to Improve Financial Reporting (https://www.sec.gov/rules/final/2009/33-9002.pdf) for details on the eXtensible Business Reporting Language (XBRL).

standardization does not necessarily directly increase the information available to investors, it makes it easier for them to acquire and process such information, consistent with our notion of transparency.

We show that such increases in fundamental transparency can make prices *less* informative about fundamentals. Higher transparency has the intended, direct effect of increasing the acquisition of fundamental information. However, because of the complementarity in learning, higher transparency also triggers more learning about the beliefs of others. Since prices reflect both types of information, when the relative rate of information acquisition about fundamentals is lower, price informativeness about fundamentals can decrease with transparency. Moreover, we find that informational efficiency is more likely to decrease with transparency when (1) fundamental transparency is already high and (2) acquiring information about other traders is relatively costly.

An alternative policy approach to address market uncertainty is the direct disclosure of public information about fundamentals, for example, by providing forward guidance (see Bernanke 2013) or disclosing bank stress test results (see Goldstein and Sapra 2014). We show that such disclosures can reduce both price informativeness and overall informational efficiency. More informative disclosures increase the amount of fundamental information available to market participants. However, this disclosure also changes investors' incentives to acquire information: acquiring additional information about fundamentals becomes less valuable, but acquiring information about other traders becomes more valuable. As a result, price informativeness can decrease with greater disclosure, and despite the direct benefit of more public information about fundamentals, aggregate informational efficiency can fall as well.

1. Related Literature

Our paper is related to the large literature on endogenous information acquisition in financial markets. The standard intuition of Grossman and Stiglitz (1980) implies that information acquisition is a strategic substitute: the benefit of learning more about fundamentals decreases as other investors learn more, since the price becomes a more informative signal about fundamentals. In contrast, a number of recent papers have identified different channels through which learning about fundamentals can be a strategic complement across investors.[6] In these papers, strategic complementarity in information acquisition typically arises either through the informativeness of the equilibrium price or because of strategic complementarities in payoffs. As an example of the first channel, Avdis (2016) presents a model in which the

[6] These papers include Froot et al. (1992), Barlevy and Veronesi (2000), Veldkamp (2006), Chamley (2007), Ganguli and Yang (2009), Garcia and Strobl (2011), Breon-Drish (2011), Goldstein et al. (2014), Goldstein and Yang (2015), and Avdis (2016).

price becomes less informative about persistent noise trading as the number of informed investors increases — as a result, acquiring fundamental information can become more valuable, as it allows informed investors to better forecast capital gains. Angeletos and La'O (2013), Benhabib et al. (2016), Sockin and Xiong (2015), and Gondhi (2017), among others, illustrate the second channel: in these models, production decisions (and consequently, payoffs) exhibit strategic complementarity; as Benhabib et al. (2016) show, this can lead to strategic complementarity in information choices. Hellwig and Veldkamp (2009) provide general conditions under which information acquisition exhibits strategic complementarity.

The notion of complementarity we analyze is fundamentally different from the one analyzed in these papers. Our analysis focuses on complementarity in learning about different payoff components (fundamental payoff vs. the beliefs of other investors) for an *individual* investor.[7] Specifically, learning about fundamentals and other investors are complements if the marginal benefit of learning more about fundamentals increases with more learning about the beliefs of other investors, and vice versa. Our notion of complementarity is closely related to general notion of Edgeworth complements in Milgrom and Roberts (1995), and does not depend on the behavior of other investors.[8] In fact, since L investors exhibit differences of opinions (and do not learn from prices) in our model, learning is neither a strategic substitute nor a strategic complement: the information choices of any L investor is unaffected by the behavior of others.

The focus on learning about multiple dimensions is similar to Goldstein and Yang (2015), who consider a setting where investors are heterogeneously informed about two components of fundamentals. In their model, when one group of investors learns more about (and trades aggressively on) the first component, the price becomes more informative about this component. This reduces uncertainty for the other group, who in turn, learn more about (and trade aggressively on) the second component of fundamentals. As a result, producing information about the two components of fundamentals is a strategic complement. We view our analysis as complementary to theirs: at the aggregate level, our papers share the result that more learning along one dimension leads to more learning along the other. However, there are important differences in the underlying mechanism and the model implications. For instance, our

[7] Like in our model, in Angeletos and La'O (2013), investors possess private information about the beliefs of other agents in the economy; however, information quality is fixed in their model, whereas in our analysis, the endogenous acquisition of information occurs in response to a change in transparency. Benhabib et al. (2016) also analyze the impact of a similar "sentiment shock," and while their model allows for endogenous information acquisition, it is limited to each firm's private productivity. Gondhi (2017) considers the information acquisition decision of firm managers along two dimensions (aggregate and idiosyncratic productivity), but finds no such complementarity.

[8] Admati and Pfleiderer (1987) study a related, though distinct, notion of complementarity: in their model, two signals are complements if the benefit of observing both signals to an investor is higher than the sum of the benefits to the same investor of observing each signal separately.

result does not rely on investors updating their beliefs using prices, although the supplementary analysis in Appendix B suggests that our results are robust to allowing them to do so.[9] Moreover, a decrease in the cost of fundamental information in Goldstein and Yang (2015) always leads to an improvement in price efficiency; importantly, this is not the case in our model.

A growing empirical and theoretical literature suggests that investors "agree to disagree" about the interpretation of public information (e.g., Kandel and Pearson 1995; Banerjee and Kremer 2010) and do not update their beliefs perfectly using the information in prices (e.g., Banerjee et al. 2009, Banerjee 2011; Eyster et al. 2015; Vives and Yang 2017). Despite the importance of higher-order beliefs in such settings, much of the literature restricts attention to the case in which investors know the beliefs (and information) of others. A notable exception is the dynamic model of Banerjee et al. (2009) in which investors are exogenously endowed with private signals about fundamentals and the beliefs of other investors.[10] Like in Banerjee et al. (2009), investors in our model learn about the beliefs of others in order to speculate against them. However, unlike the earlier paper, we explicitly model their endogenous information choice and characterize how investors trade off learning along different dimensions. Given that the literature on endogenous information acquisition has largely focused on the noisy rational expectations framework, one contribution of our paper is that it extends the scope of the analysis to a setting in which investors do not learn from prices.

Finally, our paper relates to the broad literature that studies the costs and benefits of higher transparency and disclosure. Our model is stylized to highlight a novel channel through which such policy changes affect investor behavior, and as such, abstracts from other tradeoffs already analyzed in the literature (see Bond et al. 2012; Goldstein and Sapra 2014; Goldstein and Yang 2017b for recent surveys). A subset of these papers have focused on a "crowding out" effect: greater public disclosure about fundamentals can decrease acquisition of private information (e.g., Diamond 1985; Gao and Liang 2013; Colombo et al. 2014), which in turn can reduce price informativeness and welfare. Since investors learn along multiple dimensions in our model, public disclosures about fundamentals crowd out private learning about fundamentals, but can "crowd in" private learning about the beliefs of others. Like in our paper, Dugast and Foucault (2017) show how an increase in transparency can lower the informational efficiency of prices. However, their analysis highlights an

9 Appendix B presents an extension to our model in which L investors can learn from prices. In this case, we find that for each *individual* investor learning about fundamentals and noise trading is complementary, even when they condition on the information in prices. Moreover, consistent with the standard intuition of Grossman and Stiglitz (1980), learning about fundamentals is a *strategic substitute across* investors.

10 In Banerjee et al. (2009), investors agree to disagree about fundamentals (and so do not condition on prices to update their beliefs about fundamentals), but update their beliefs about the average valuation of other investors in order to speculate against them. Ganguli and Yang (2009) and Marmora and Rytchkov (2016) model the analogous learning problem in noisy rational expectations models.

intertemporal crowding-out effect. When early, low-precision signals become cheaper, prices are more likely to reflect this information, which increases informativeness in the short-run; on the other hand, more informative short-run prices discourages the acquisition of late, high-precision signals, which can decrease efficiency in the long-run. Since L investors' information acquisition only affects prices at one date, the distinction between long-run and short-run efficiency does not arise in our setting.[11] Instead, we analyze how transparency affects learning across dimensions, and focus on the resultant impact of speculative motives on price efficiency.

2. Model

2.1 Model setup

There are four dates (i.e., $t \in \{0,1,2,3\}$) and two assets. The risk-free asset is the numeraire. The risky asset is in zero net supply and pays a liquidating dividend ϕ at date 3.[12] There is a unit continuum of both short-lived (S) and long-lived (L) investors; each type is of equal measure. These types differ in their interpretation of a public signal, F, which is revealed prior to trading at date 2. For instance, the public signal may represent an earnings announcement by a firm. The conditional expectation of fundamentals, given the signal, is equal to F, that is, $\mathbb{E}[\phi \big| F] = F$.

Short-lived investors (indexed by $s \in S$) can only trade at date 2 and potentially hold incorrect beliefs about the joint distribution of $\{F, \phi\}$. Specifically, for each $s \in S$, $\mathbb{E}_s[\phi \big| F] = \alpha \mathbb{E}[\phi \big| F]$, where α reflects S investors' interpretation of the public signal F. We assume that α is independent of F and is not known with certainty before date 2.[13]

Long-lived investors (indexed by $l \in L$) can trade at dates 1 and 2 and hold the correct beliefs about the joint distribution of $\{F, \phi\}$ (i.e., for each $l \in L$, $\mathbb{E}_l[\phi \big| F] = \mathbb{E}[\phi \big| F]$). Moreover, L investors can acquire private information about both fundamentals (i.e., the liquidating dividend) and the beliefs of others (i.e., S investors' interpretation of the public signal). Before trading at date 1, each investor $l \in L$ observes her private signals $\{f_l, a_l\}$ about $\{F, \alpha\}$, respectively. These private signals are independent of each other and conditionally independent across investors. However, each investor l

[11] Alternatively, one could consider this distinction in a natural extension of our model by comparing informational efficiency at date 0 versus date 1. To do so, one would augment the model in Section 5 with another round of trading at date zero. In this case, the date zero price would reflect the price of the asset conditional on date zero public information (i.e., the public signal Y disclosed), while as before, the date one price would also incorporate the private information chosen by investors. In this setting, an increase in public disclosure naturally leads to higher short-run efficiency (because the date 0 price would become more informative about fundamentals), but can lead to lower long-run (in this case, date 1) efficiency, as the results of Section 5 suggest.

[12] Assuming that the supply is nonzero does not alter our key mechanism—complementarity in learning—but adds unnecessary complexity to the expressions that follow.

[13] As we discuss in Section 2.3, allowing S investors to trade at date 1 does not qualitatively change our results, but makes the analysis less tractable.

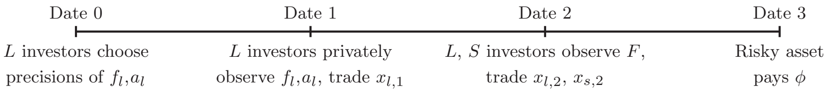


Figure 1
Time line of events

believes that for any other investor $k \neq l$, the signals $\{f_k, a_k\}$ are completely uninformative. At date 0, each investor $l \in L$ optimally chooses the precision of her private signals subject to a cost function $C(\cdot)$.

Each investor $i \in \{L, S\}$ optimally chooses her demand for the risky asset ($x_{i,t}$) to maximize the expectation of her date 3 wealth given her beliefs. All investors are subject to a quadratic inventory cost λ, which ensures optimal demands are finite. The price of the risky asset at dates 1 and 2 is determined by the market clearing conditions:

$$\int_{s\in S} x_{s,2} ds + \int_{l\in L} x_{l,2} dl = 0, \quad \text{and} \quad \int_{l\in L} x_{l,1} dl = 0, \tag{1}$$

respectively. Figure 1 summarizes the evolution of the model.

2.2 Financial market equilibrium

At date 2, investor i's optimal demand is given by

$$x_{i,2} = \arg\max_x \mathbb{E}_i[x(\phi - P_2)|F] - \tfrac{\lambda}{2}x^2, \tag{2}$$

$$= \tfrac{1}{\lambda}(\mathbb{E}_i[\phi|F] - P_2). \tag{3}$$

In particular, the public signal F subsumes the private information that L investors have about fundamentals. Since $\mathbb{E}_i[\phi|F] = \mathbb{E}_s[\phi|F]$ for all $s \in S$ and $\mathbb{E}_i[\phi|F] = \mathbb{E}_l[\phi|F]$ for all $l \in L$, the market clearing condition implies

$$P_2 = \tfrac{1}{2}(\mathbb{E}_l[\phi|F] + \mathbb{E}_s[\phi|F]) = AF, \tag{4}$$

where $A \equiv (1+\alpha)/2$.

At date 1, investor l's optimal demand is given by

$$x_{l,1} = \arg\max_x \mathbb{E}_l\left[\mathbb{E}_l[x_{l,2}(\phi - P_2)\big|F] - \tfrac{\lambda}{2}x_{l,2}^2 + x(P_2 - P_1) - \tfrac{\lambda}{2}x^2\big|f_l, a_l\right], \tag{5}$$

$$= \arg\max_x \mathbb{E}_l\left[\tfrac{1}{2\lambda}(\mathbb{E}_l[\phi|F] - P_2)^2 + x(P_2 - P_1) - \tfrac{\lambda}{2}x^2\big|f_l, a_l\right], \tag{6}$$

$$= \tfrac{1}{\lambda}(\mathbb{E}_l[A|a_l]\mathbb{E}_l[F|f_l] - P_1), \tag{7}$$

where the last equality follows from $\mathbb{E}_l[P_2|f_l, a_l] = \mathbb{E}_l[A|a_l]\mathbb{E}_l[F|f_l]$, because each investor's private signals, f_l and a_l, are conditionally independent. Investor l does not condition on P_1 when updating her beliefs about P_2 because she exhibits differences of opinions: she believes the private information of other investors is uninformative and, consequently, so is the price. The date 1 market clearing condition implies that

$$P_1 = \int_{l\in L} \mathbb{E}_l[P_2|f_l, a_l] dl = \int_{l\in L} (\mathbb{E}_l[A|a_l] \times \mathbb{E}_l[F|f_l]) dl. \tag{8}$$

2.3 Discussion of assumptions

The specific assumptions we make are for analytic tractability and to highlight the underlying mechanism in the clearest manner.

By assuming that each investor believes that others' signals are uninformative, we abstract away from how she updates her beliefs using the date 1 price. Similarly, the assumption that S investors are short-lived implies that L investors do not learn about A from the date 1 price. These assumptions highlight that our main mechanism—complementarity in learning—does not rely on investors' ability to extract information from prices. As such it is very different from the strategic complementarity across investors that is widely studied in the literature. In Appendix B, we extend our model to allow L investors to update their beliefs about F and A from the date 1 price by introducing an aggregate noisy supply of the asset. We characterize the conditions under which a unique, noisy rational expectations equilibrium exists at date 1, but the equilibrium price cannot be solved for explicitly. This limits our ability to analytically characterize conditions for complementarity or solve for the optimal acquisition of private information. However, numerical analysis suggests that our main conclusions are robust to allowing learning from prices—that is, for each investor, learning about F and A is complementary—and price efficiency can decrease with transparency.

Quadratic transaction costs provide a transparent way to ensure that each investor's demand for the risky asset is finite (e.g., Vives 2011; Rostek and Weretka 2012; Duffie and Zhu 2017). We expect our results would be similar in a setting with risk-averse investors, but given the nonlinearity in prices, an analytic characterization of our results would be more difficult.

To pin down ideas, we allow L investors to acquire information about a particular aspect of S investors, namely, their interpretation of the public signal F. For the main implications of our analysis, this choice is not important. For instance, one could assume instead that L investors know the interpretation α, but face uncertainty about the mass of other investors.[14] The key feature of the resultant financial equilibrium is that the price is a nonlinear combination of fundamental information and beliefs about the behavior of other investors.

While made for tractability, many of these assumptions are also empirically relevant. A growing body of empirical evidence, both direct (e.g., Kandel and Pearson 1995; Cookson and Niessner 2016) and indirect (e.g., Chae 2005; Banerjee and Kremer 2010), suggests that investors exhibit differences of opinions. Moreover, models that incorporate differences of opinions have proved to be insightful in explaining empirically observed patterns in trading volume (e.g., Kandel and Pearson 1995; Banerjee and Kremer 2010) and return dynamics (e.g., Scheinkman and Xiong 2003; Banerjee et al. 2009) that have been challenging in the rational expectations framework. Our analysis suggests

[14] One could also model uncertainty along both dimensions at the cost of tractability.

that incorporating this feature also has important implications for the evaluation of policy decisions.

The assumption that S investors only trade the risky asset concurrent with the public announcement is consistent with evidence of intermittent participation by investors, as documented by Frazzini and Lamont (2007). Like in Kandel and Pearson (1995), they argue that earnings announcements may spark increased disagreement amongst investors; further, they argue that this news also grabs the attention of those who were not following the stock. Finally, while we argue that some investors (S investors) trade upon announcement (like in Huang et al. 2016; Kaniel et al. 2012), there also exists a subset of investors (L investors in our model) who can learn about the news before the announcement, consistent with the evidence of Campbell et al. (2009), Hendershott et al. (2015), and Kadan et al. (2017).

This assumption is also consistent with evidence that while investor attention increases prior to an earnings announcement, it spikes concurrent with such news (e.g., Drake et al. 2012). The magnitude of this attention affects how strongly the price responds to the information contained in the announcement. Specifically, low levels of attention and media coverage are associated with stronger post-announcement drift, that is, an “underreaction" to such information (e.g., Curtis et al. 2016; Hirshleifer et al. 2009; Peress 2008). At the same time, evidence suggests that investors’ attention and media coverage can also generate an “overreaction" to information, because both are positively associated with long-term price reversals (e.g., Da et al. 2011, Hillert et al. 2014). Moreover, there is direct evidence that media coverage, by drawing investor attention to an asset, generates increased trading by individuals (e.g., Barber and Odean 2008) as well as some institutions (e.g., Fang et al. 2014). As expected, given this evidence, many institutions actively monitor investor attention when making investment decisions.[15]

3. Information Acquisition and Transparency

3.1 Value of information and complementarity in learning

At date 0, each long-term investor chooses the precision of her private signals f_l and a_l to maximize her expected gains from trade, $V_{l,0}$:

$$V_{l,0} \equiv \mathbb{E}_{l,0}\left[x_{l,2}(\phi - P_2) - \tfrac{\lambda}{2}x_{l,2}^2 + x_{l,1}(P_2 - P_1) - \tfrac{\lambda}{2}x_{l,1}^2\right] \tag{9}$$

$$= \mathbb{E}_{l,0}\left[\tfrac{1}{2\lambda}(\mathbb{E}_l[\phi|F] - P_2)^2 + \tfrac{1}{2\lambda}(\mathbb{E}_l[P_2|f_l, a_l] - P_1)^2\right] \tag{10}$$

An investor’s expected gains are driven by her ability to trade on information about the risky asset that she believes is not contained in the price. Specifically,

15 As noted by a managing director at Samsara Investments, “Our strategy ... uses all sources of real-time fundamental information (news, SEC filings, etc.) Sentiment data is a perfect fit to our strategy, and it helps us achieve much stronger risk-adjusted performance, when layered into our previous data sources” (Aroomoogan 2015).

her expected trading gain increases in the absolute difference in her beliefs about the next period's payoff (i.e., $\mathbb{E}_l[\phi|F]$ and $\mathbb{E}_l[P_2|f_l,a_l]$) and the market's expectations (i.e., P_2 and P_1, respectively.) Intuitively, she believes that she can "beat the market" by anticipating future payoffs better than other, "uninformed" investors.

Each investor is infinitesimal and so her individual information choices do not affect the distribution of prices. As a result, the information choice of investor l only affects the second term of the above expression (i.e., $(\mathbb{E}_l[P_2|f_l,a_l]-P_1)^2$). Further, each investor believes that P_1 is independent of f_l and a_l, because of differences of opinion. With this simplification, and using the law of iterated expectations, we can express the total expected trading gain for investor l as

$$V_{l,0}=\frac{1}{2\lambda}\left(\bar{V}+\mathbb{E}_{l,0}\left[\mathbb{E}_l[A|a_l]^2\times\mathbb{E}_l[F|f_l]^2\right]\right), \tag{11}$$

where $\bar{V}$ is given by

$$\bar{V}\equiv\mathbb{E}_{l,0}\left[(\mathbb{E}_l[\phi|F]-P_2)^2\right]+\mathbb{E}_{l,0}[P_1^2]-2\mathbb{E}_{l,0}[P_1]\mathbb{E}_{l,0}[\phi]\mathbb{E}_{l,0}[A],$$

and does not depend on investor l's choice of precisions. The characterization in (11) allows us to highlight the value of information in our model. We begin with a definition.

Definition 1. Learning exhibits *complementarity* if acquiring more information along one dimension increases the marginal value of learning along another dimension.

We provide a formal characterization of this definition in Proposition 1 after the introduction of additional notation. Using the above definition, however, we can immediately make a number of intuitive observations. First, Equation (11) implies that learning about F and A is generically valuable.[16] Note that $V_{l,0}$ contains an expectation of a convex function of $\mathbb{E}_l[F|f_l]$ and $\mathbb{E}_l[A|a_l]$. By the law of total variance, more informative signals about F and A increase the variance of these conditional expectations which leads to an increase in $V_{l,0}$.[17] Intuitively, by acquiring more informative signals about F and A, each investor believes she is increasing her informational advantage relative to the rest of the market, and this increases her expectation of trading gains.

Second, Equation (11) implies that learning about F and A always exhibits complementarity. Specifically, the marginal value of learning more about F

16 In the degenerate case in which the unconditional means of F and A are both zero and the investor does not learn along one of the two dimensions, the value of learning along the other dimension is zero.

17 Recall that the law of total variance implies

$$\mathrm{var}[X]=\mathbb{E}[\mathrm{var}[X|Y]]+\mathrm{var}\left[\mathbb{E}[X|Y]\right].$$

When Y is a more informative signal about X, we expect $\mathrm{var}[X|Y]$ to be lower, which implies that $\mathrm{var}[\mathbb{E}[X|Y]]$ must be higher.

(i.e., increasing $\mathbb{E}_{l,0}(\mathbb{E}_l[F|f_l]^2)$ is higher when the signal about A is more informative (i.e., when $\mathbb{E}_{l,0}(\mathbb{E}_l[A|a_l]^2)$ is higher). Complementarity arises in our model because the price at date 2 is a nonlinear function of investor information about fundamentals and the beliefs of other traders. From an investor's perspective, the value of an informational advantage along one dimension is amplified by the informational advantage along the other because her payoff P_2 is a nonlinear interaction of the two. In contrast, if the date 2 price were linear in F and A (like in standard models), complementary would not arise because the incremental value from learning along each dimension is unaffected by how much is learned along the other dimension—we establish this formally in Appendix B.2. Moreover, the above characterization suggests that a similar nonlinearity in payoffs and, consequently, complementarity in learning may arise more generally.[18] Consequently, our results may extend beyond the specific setting we consider in this paper.

Finally, we emphasize that our notion of complementarity captures the value of learning along multiple dimensions for each individual investor. As we discussed in Section 1, this is in contrast to the growing literature which demonstrates how learning about fundamentals can be a strategic complement across investors. In our setting, an L investor's information choices do not depend on the choices of other L investors, and so learning is not a strategic substitute or a strategic complement. Our notion of complementarity does not rely on investors' ability to condition on prices, and as such, is a fundamentally distinct mechanism.[19] As a result, our analysis of how transparency and disclosure affect informational efficiency focuses on a novel channel not considered by this earlier work.

3.2 The effect of transparency on learning

To formally characterize the optimal information acquisition decision of investors and how it is affected by transparency, we make the following assumptions. We make these specific choices to ensure tractability.

3.2.1 Joint distribution of payoffs and signals. Let $\phi = F + u$, where $\mathbb{E}[u] = 0$, $\mathbb{E}[u^2] = \frac{1}{\tau_u} < \infty$ and u is independent of F. Let $\log(F) = f - \frac{1}{2\tau_0}$, where $f \sim$

[18] For instance, in many standard settings, prices reflect information about cash flows and discount rates in an inherently nonlinear manner. To fix ideas, suppose the price of a stream of cash flows is given by its discounted present value, that is, $P_t = \mathbb{E}_t\left[\sum_{s>t} \frac{D_s}{(1+r_s)^{s-t}}\right]$. In this case, beliefs about future cash flows (i.e., D_s) and discount rates (i.e., r_s) interact nonlinearly. In an earlier version of the paper, we considered another setting in which such nonlinearity arises naturally. Our analysis focused on a setting in which liquidity providers can choose to learn about both the value of a risky asset (fundamentals) and the intensity of price-dependent liquidity demand (behavior of others). In this setting, learning about fundamentals and liquidity demand was complementary.

[19] The analysis in Appendix B suggests that allowing L investors to learn from prices does not affect the complementarity in learning that we emphasize. Interestingly, however, in this more general setting, learning about fundamentals is a strategic substitute, as it is in most standard models.

$\mathcal{N}(0, \frac{1}{\tau_0})$, and suppose the private signal acquired by investor l is of the form:

$$f_l = f + \varepsilon_l, \quad \text{where } \varepsilon_l \sim \mathcal{N}\left(0, \frac{1}{\tau_l}\right). \tag{12}$$

This implies that, conditional on her private signal, investor l's beliefs about fundamentals are given by

$$\mathbb{E}_l[f\,|\,f_l] = \frac{\tau_l}{\tau_0+\tau_l} f_l, \quad \mathrm{var}_l[f\,|\,f_l] = \frac{1}{\tau_0+\tau_l} \tag{13}$$

$$\Rightarrow \mathbb{E}_l[F\,|\,f_l] = e^{\frac{\tau_l}{\tau_0+\tau_l} f_l + \frac{1}{2(\tau_0+\tau_l)} - \frac{1}{2\tau_0}}. \tag{14}$$

Similarly, we assume that $\log(A) = a - \frac{1}{2\rho_0}$, where $a \sim \mathcal{N}(0, \frac{1}{\rho_0})$. This ensures that $A > 0$ and implies that the unconditional mean of A is one, that is, a priori, L investors expect S investors to interpret the public signal correctly, on average.[20] Again, suppose the private signals about A are conditionally normal:

$$a_l = a + \xi_l, \quad \text{where } \xi_l \sim \mathcal{N}\left(0, \frac{1}{\rho_l}\right). \tag{15}$$

As a result, conditional on her private signal, investor l's beliefs about A are given by:

$$\mathbb{E}_l[a|a_l] = \frac{\rho_l}{\rho_0+\rho_l} a_l, \quad \mathrm{var}_l[a|a_l] = \frac{1}{\rho_0+\rho_l} \tag{16}$$

$$\Rightarrow \mathbb{E}_l[A|a_l] = e^{\frac{\rho_l}{\rho_0+\rho_l} a_l + \frac{1}{2(\rho_0+\rho_l)} - \frac{1}{2\rho_0}}. \tag{17}$$

3.2.2 Cost function. We assume that the cost function $C(\tau_l, \rho_l, h)$ is increasing and separable in precisions τ_l and ρ_l, that is,[21]

$$\frac{\partial C}{\partial \tau_l} > 0, \quad \frac{\partial C}{\partial \rho_l} > 0, \quad \text{and} \quad \frac{\partial^2 C}{\partial \rho_l \partial \tau_l} = 0.$$

We denote *fundamental transparency* by the parameter h. In particular, the marginal cost of acquiring fundamental information is decreasing in h, that is,

$$\frac{\partial^2 C}{\partial \tau_l \partial h} < 0.$$

Our notion of transparency distinguishes our analysis from other models in the literature. We focus on the effect of regulation which alters the ease of

[20] This assumption is without loss of generality. It would be straightforward to alter our distributional assumptions to allow S investors to either underreact or overreact, on average, to the public signal.

[21] The assumption that $\frac{\partial^2 C}{\partial \rho_l \partial \tau_l} = 0$ ensures that there is no complementarity/substitutability in learning driven by the cost function. This allows us to focus on the complementarity in learning that endogenously arises due to speculative incentives, without potentially confounding effects that depend on the specific cost function. Since learning about fundamentals and other investors is complementary in our setting, it seems reasonable to conjecture that an information producer may choose to bundle these types of information (and the resultant cost is no longer separable). However, given the lack of empirical evidence for such bundling of fundamental financial information and the behavior of others, we defer this analysis to future work.

acquiring (i.e., the cost of) information. Modeling the policy change as a change in the cost of acquiring information seems appropriate for a number of recent policy changes (e.g., Title IX in Dodd-Frank, Sarbanes-Oxley, and the 2009 SEC mandate on the adoption of the XBRL). In these cases, in addition to any new information which was made available, the regulation and standardization improved investors' ease of access to *existing* public information. In particular, these changes made it easier for investors to process the available information. We distinguish the effect of such changes from that of greater public disclosure, which involves the direct provision of fundamental public information by policymakers (e.g., forward guidance, bank stress tests). We turn to the impact of disclosure in Section 5.

Given the assumptions above, the following result characterizes the optimal choice of precisions.

Proposition 1. The optimal choice of precisions τ_l and ρ_l maximize the following objective:

$$\tau_l, \rho_l = \arg\max_{\tau_l, \rho_l} e^{\frac{1}{\tau_0} - \frac{1}{\tau_0+\tau_l} + \frac{1}{\rho_0} - \frac{1}{\rho_0+\rho_l}} - C(\tau_l, \rho_l, h). \tag{18}$$

If $C(\tau_l, \rho_l, h)$ is convex and both τ_0 and $\rho_0 > 1$, then there exists a unique choice of precisions $\{\tau_l(h), \rho_l(h)\}$, parametrized by transparency, h, that maximizes (18). Furthermore,

(a) Learning exhibits complementarity, that is, $\frac{\partial^2 V_{l,0}}{\partial \tau_l \partial \rho_l} > 0$.

(b) An increase in transparency (h) leads to more learning about both fundamentals and other investors, that is, $\{\tau_l(h), \rho_l(h)\}$ are nondecreasing in h.

Consistent with our argument in the general case, learning exhibits complementarity: the marginal value of learning about fundamentals ($\frac{\partial V_{l,0}}{\partial \tau_l}$) is increasing in the precision of private information about the beliefs of others (ρ_l), since

$$\frac{\partial^2 V_{l,0}}{\partial \tau_l \partial \rho_l} = \tilde{V}_{l,0} \frac{1}{(\tau_0+\tau_l)^2(\rho_0+\rho_l)^2} > 0.$$

Moreover, since the cost function is separable in τ_l and ρ_l, this implies that an increase in fundamental transparency, which leads to more learning about fundamentals, also leads to more learning about other investors. As we will show in the next section, it is this channel through which fundamental transparency can lower informational efficiency.

4. Informational Efficiency

To characterize the effects of a change in transparency, we focus on its impact on informational efficiency. Informational efficiency is not only itself of general interest to academics, practitioners and regulators, but is often closely related to real (allocative, or Pareto) efficiency in more general settings.[22] Moreover, informational efficiency is arguably a less ambiguous object of analysis than welfare in our setting, since there is no agreed upon welfare criterion when investors exhibit differences of opinions (see the discussion in Brunnermeier et al. (2014)). We note, however, that in Appendix B.1, we will characterize the impact of transparency on a particular specification of welfare. We find that above a certain threshold, welfare necessarily decreases with transparency in our setting.

We focus on the symmetric equilibrium in which each long-lived investor optimally chooses the same precision for her private signals, and denote the optimal level of precisions by $\tau = \tau_l$ and $\rho = \rho_l$.[23] We define informational efficiency as follows.

Definition 2. The *informational efficiency* of the date 1 price is $\mathcal{E} = -\mathbb{E}_0\left[(\phi - \mathbb{E}[\phi|P_1])^2\right]$.

Intuitively, informational efficiency captures, in expectation, how much information about fundamentals can be extracted from the date 1 price. It is the precision of an uninformed investor's forecast of fundamentals, that is, the conditional expectation of fundamentals, given the date 1 price. The analogous measure of informational efficiency with respect to the date 2 price does not depend on the investors' informational choices and so is unaffected by changes in transparency. Given our distributional assumptions, we can derive the following closed-form expression for informational efficiency in terms of the quality of the information possessed by investors.

Proposition 2. Given the optimal choice of (equilibrium) precisions $\{\tau, \rho\}$, efficiency is given by

$$\mathcal{E} = -\left(e^{\frac{1}{\tau_0}}\left(1 - e^{-\frac{1}{\tau_0+\tau_p}}\right) + \frac{1}{\tau_u}\right), \tag{19}$$

where $\tau_p = \rho_0\left(\frac{\tau}{\tau_0+\tau}\frac{\rho_0+\rho}{\rho}\right)^2$. In particular, efficiency increases with more learning about fundamentals (τ), but decreases as more information about other investors is acquired (ρ).

Proposition 2 highlights how efficiency depends on both the prior distributions and the optimal choice of precisions. As expected, efficiency is higher when

[22] For instance, Chen et al. (2007) provide empirical evidence consistent with the hypothesis that managers use the information in market prices when making investment decisions, and Goldstein et al. (2013), Goldstein and Yang (2017a), and others link the informational efficiency of prices to allocative or real efficiency.

[23] Since L investors exhibit differences of opinion and believe that other investors are uninformed, each has an incentive to learn about both F and A. A model in which investors can update their beliefs from prices may lead to asymmetric equilibria, in which some investors specialize in acquiring information from fundamentals while others choose to speculate on the behavior of other investors. We hope to explore this in future work.

the prior variance about ϕ is lower (i.e., efficiency is increasing in both τ_u and τ_0). Efficiency also increases with τ_p, which captures the precision of the price as a signal about F (and therefore ϕ). Intuitively, the price is a more precise signal about fundamentals when investors learn more about the terminal dividend (i.e., τ is higher) and less about others (i.e., ρ is lower). For instance, as more information about the beliefs of S investors is impounded into the price by investors, it becomes more difficult to disentangle whether a "high" price is a function of (1) strong fundamentals or (2) the anticipation of investors overreacting to the public announcement. As a result, efficiency always increases with learning about fundamentals and decreases when investors learn more about others.

Given the above characterization, one might expect that increasing fundamental transparency would necessarily lead to higher efficiency, because investors choose to learn more about fundamentals. However, as the result below highlights, this is not always the case.

Theorem 1. Efficiency decreases with an increase in transparency when

$$\frac{\rho_0}{\rho_0+\rho(h)}\frac{\rho_h}{\rho(h)}-\frac{\tau_0}{\tau_0+\tau(h)}\frac{\tau_h}{\tau(h)}>0, \tag{20}$$

where $\tau_h=\frac{\partial\tau(h)}{\partial h}$ and $\rho_h=\frac{\partial\rho(h)}{\partial h}$.

Increasing transparency has the intended, direct effect: investors learn more about fundamentals which, all else equal, increases efficiency. As a result, in the absence of complementarity (when $\rho_h=0$), more transparency would unambiguously increase efficiency. The complementarity in learning, however, leads to an unintended, indirect effect. Learning more about fundamentals makes learning about other investors more valuable. This indirect channel provides a countervailing effect on efficiency.

The relative rate of information acquisition determines which effect dominates. When investors choose to learn proportionally more about the beliefs of others, given their existing information (i.e., condition (20) holds), the indirect effect dominates and efficiency falls. This is more likely to occur when fundamental transparency is already high, because increasing transparency leads to a modest increase in fundamental information, but can generate a relatively large increase in the acquisition of information about others.

Our analysis also suggests that a *decrease* in transparency about other investors could also lower efficiency.[24] While such policies make it more difficult to speculate on the behavior of other investors, the complementarity in learning implies that there is a corresponding decrease in learning about fundamentals. If the relative decline in learning about fundamentals is

[24] Given the symmetry of the expressions, the proof is analogous to that of Theorem 1.

sufficiently large, then efficiency would fall. This suggests that recent proposals to delay or limit access to information about the activity of other traders (e.g., Harris 2013) may have unintended, negative consequences.

Theorem 1 describes the necessary and sufficient conditions under which efficiency falls with an increase in transparency. Our characterization of these conditions relies upon not just the assumed parameters of the model, but crucially upon the endogenous choice of optimal precisions made by investors. It is essential, then, that we demonstrate that the endogenous response of the investor can meet these conditions. We take up this exercise next.

4.1 An example

To characterize the conditions for Theorem 1 as an explicit function of primitives, we must specify a cost function. For tractability, suppose the cost function is

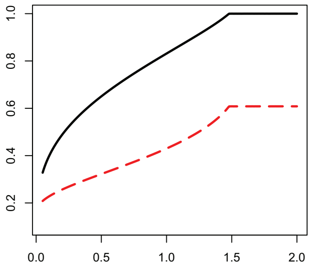
$$C(\tau_l,\rho_l,h)=e^{\frac{1}{\tau_0}+\frac{1}{\rho_0}}\left[\frac{1}{h}\frac{\left(\frac{\tau_l}{\tau_0+\tau_l}\right)^{m+1}}{m+1}+\frac{1}{g}\frac{\left(\frac{\rho_l}{\rho_0+\rho_l}\right)^{n+1}}{n+1}\right]. \tag{21}$$

for $m,n>0$. This is a common specification: the cost of acquiring information is proportional to the relative precision of this information (i.e., $\frac{\tau_l}{\tau_0+\tau_l}$, and $\frac{\rho_l}{\rho_0+\rho_l}$) raised to a power. When $m,n>1$, the initial marginal cost of acquiring information is zero. Moreover, if $(m\tau_0-1)(n\rho_0-1)>1$, then there exists a unique, symmetric equilibrium.[25] For the following result, we assume that both conditions hold.

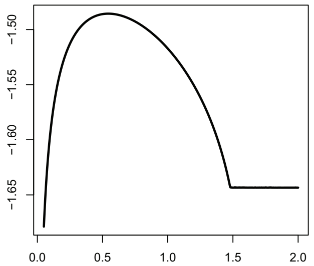
Proposition 3. Suppose the cost function is given by (21), and a unique solution to (18) exists. If $m>n$ and $\frac{\rho_0+\tau_0}{\rho_0\tau_0}\geq n$, then there exists a $\bar{g}(\tau_0,\rho_0,n)$ such that for all $g<\bar{g}(\tau_0,\rho_0,n)$, efficiency initially increases and then decreases in fundamental transparency.

Figure 2 numerically illustrates the nonmonotonicity in efficiency described in Proposition 3. Complementarity in learning implies that increasing fundamental transparency not only increases learning about fundamentals, but also increases learning about others. For relatively low values of fundamental transparency, the rate of learning about fundamentals increases faster than the rate of learning about others, and as a result, efficiency increases with transparency. However, once learning about fundamentals is sufficiently high, the relative rate of learning about others is higher, and efficiency begins to fall. When transparency is sufficiently high, investors essentially acquire as much information as they can about fundamentals, and so the optimal choice τ_l is effectively unresponsive

25 This condition differs from that specified in Proposition 1 because the cost function is concave for large enough values of τ_l and ρ_l.



(a) $\frac{\tau}{\tau_0+\tau}$ (solid), $\frac{\rho}{\rho_0+\rho}$ (dashed) versus h



(b) Efficiency $\mathcal{E}$ versus h

Figure 2
Optimal precisions and efficiency as a function of transparency h
The figure plots optimal precision choices for fundamental information (i.e., $\frac{\tau}{\tau_0+\tau}$, solid) and information about others (i.e., $\frac{\rho}{\rho_0+\rho}$, dashed) and efficiency as a function of fundamental transparency h. Other parameter values are set to: $\tau_0=\rho_0=1$ and $g=0.9$, $m=4$ and $n=1$, where the cost function is given by Equation (21).

to a change in h. In this region, the incentive to acquire information about others is essentially constant, and consequently, efficiency does not respond to transparency.

The above highlights the main result of our analysis. In the presence of speculative opportunities, learning about fundamentals and the behavior of other investors can be complementary, and an increase in transparency can be counterproductive. If, in response, the rate of learning about others exceeds the rate of learning about fundamentals, efficiency can fall with transparency. This is more likely to occur when investors already choose to acquire significant information regarding fundamentals, but find learning about others sufficiently costly.

5. Public Disclosure

In addition to affecting transparency, policymakers can also alter the information environment by directly disclosing public information about fundamentals. This section considers the impact of such policies. First, we establish conditions under which our main results about complementarity and the effects of transparency remain unchanged despite the inclusion of such disclosures. Second, we show that when investors endogenously choose what information to acquire, increased disclosure can lower informational efficiency.

To study the effect of disclosure, we introduce a public signal about fundamentals, Y, given by

$$Y = f + y, \quad \text{where} \quad y \sim \mathcal{N}\left(0, \frac{1}{\tau_y}\right).$$

We assume that Y is observable before trading at date 1, and importantly, that long-lived investors know the distribution of Y before making their information acquisition decisions at date 0.

Under these assumptions, it is immediate that the optimal demand by investors at date 2 is unchanged. This implies that, like in the benchmark model, the date 2 price is given by $P_2 = AF$. However, the date 1 beliefs of $l \in L$ investors now depend on Y. Specifically, while $\mathbb{E}_l[A|a_l]$ remains unchanged, investors condition on their private signals and the public signal to update their beliefs about fundamentals. As a result, the market clearing price at date 1 is given by

$$P_1 = \int_{l \in L} (\mathbb{E}_l[A|a_l] \times \mathbb{E}_l[F|f_l, Y])dl \tag{22}$$

5.1 Optimal information acquisition

As before, we denote each long-lived investor's expected trading gain by $V_{l,0}$, and the optimal choice of precisions maximizes $V_{l,0}$ subject to the cost function $C(\tau_l, \rho_l, h)$. The following result characterizes this optimization problem in the presence of public disclosure.

Proposition 4. The optimal choice of precisions τ_l and ρ_l maximize the following objective:

$$\tau_l, \rho_l = \arg\max_{\tau_l, \rho_l} e^{\frac{1}{\tau_0} - \frac{1}{\tau_0 + \tau_y + \tau_l} + \frac{1}{\rho_0} - \frac{1}{\rho_0 + \rho_l}} - C(\tau_l, \rho_l, h) \tag{23}$$

If $C(\tau_l, \rho_l, h)$ is convex and both τ_0 and $\rho_0 > 1$, then there exists a unique choice of precisions $\{\tau_l(h), \rho_l(h)\}$, parametrized by transparency h, that maximizes (23). Furthermore,

(a) Learning exhibits complementarity.

(b) An increase in transparency leads to more learning about both fundamentals and the beliefs of other investors, that is, $\{\tau_l(h), \rho_l(h)\}$ are nondecreasing in h.

(c) Higher disclosure increases the marginal value of learning about other investors, but decreases the marginal value of learning about fundamentals.

The above result highlights how public disclosure alters the relative value of each type of private information. First, learning about fundamentals and the beliefs of others is complementary even in the presence of disclosures about fundamentals. Second, while increasing disclosure (i.e., increasing τ_y) increases the marginal value of learning about other traders (i.e., $\frac{\partial^2 V_{l,0}}{\partial \tau_y \partial \rho_l} > 0$), increasing disclosure can decrease the marginal value of learning about fundamentals. Specifically, note that

$$\frac{\partial^2 V_{l,0}}{\partial \tau_y \partial \tau_l} = \tilde{V}_{l,0} \frac{1 - 2(\tau_0 + \tau_y + \tau_l)}{(\tau_0 + \tau_y + \tau_l)^4},$$

which is negative unless $\tau_0 + \tau_y + \tau_l < 1/2$. Under the sufficiency condition for existence and uniqueness in Proposition 4, this implies that increasing public disclosure decreases the value of acquiring private information about fundamentals.

This result is reminiscent of results in the literature in which public information can "crowd out" private information (e.g., Diamond (1985)). As Equation (23) highlights, the expected value of learning about fundamentals depends on the total learning from public and private signals—recall that $\frac{1}{\tau_0+\tau_l+\tau_y}$ is the posterior variance about f given private and public information. In this sense, public disclosure and private fundamental information are substitutes. In contrast, public disclosure and learning about others is complementary (like in Boot and Thakor 2001); as a result, disclosure "crowds in" more private information acquisition about other investors. As we will characterize next, this implies that increasing disclosure can decrease efficiency.

5.2 Effect of disclosure on efficiency

To account for the presence of the public signal, we now generalize both our definition and analytical characterization of efficiency.

Definition 3. The *informational efficiency* of the date 1 public information is given by $\mathcal{E} = -\mathbb{E}_0\left[(\phi - \mathbb{E}[\phi|P_1, Y])^2\right]$.

The updated definition reflects that there are two sources of fundamental information in the economy: public disclosure and the price of the risky asset. Given our distributional assumptions, the next result characterizes efficiency as a function of parameters and the equilibrium information acquisition decisions of investors.

Proposition 5. Given the optimal choice of (equilibrium) precisions $\{\tau, \rho\}$, efficiency is given by

$$\mathcal{E} = -\left(e^{\frac{1}{\tau_0}}\left(1 - e^{-\frac{1}{\tau_0+\tau_y+\tau_p}}\right) + \frac{1}{\tau_u}\right), \tag{24}$$

where $\tau_p = \rho_0\left(\frac{\tau}{\tau_0+\tau+\tau_y}\frac{\rho_0+\rho}{\rho}\right)^2$. In particular, efficiency increases with more learning about fundamentals (τ) and with greater disclosure (higher τ_y), but decreases with more learning about others (ρ).

The general notion of efficiency captures the direct, intended effect of increasing disclosure: with more public information, decision makers face less uncertainty about fundamentals. However, in the presence of endogenous learning, higher disclosure encourages learning about other investors, but discourages acquisition of fundamental information. As a result, disclosure has an indirect effect of reducing efficiency. The following result characterizes conditions under which increasing disclosure is counterproductive.

Theorem 2. Suppose the optimal choice of equilibrium precisions can be characterized by differentiable functions of transparency h and τ_y. Then, efficiency decreases with an increase in transparency when

$$\frac{\rho_0}{\rho_0+\rho}\frac{\rho_h}{\rho}-\frac{\tau_0+\tau_y}{\tau_0+\tau_y+\tau}\frac{\tau_h}{\tau}>0, \tag{25}$$

where $\tau_h=\frac{\partial\tau(h)}{\partial h}$ and $\rho_h=\frac{\partial\rho(h)}{\partial h}$. Moreover, efficiency can decrease with higher disclosure when

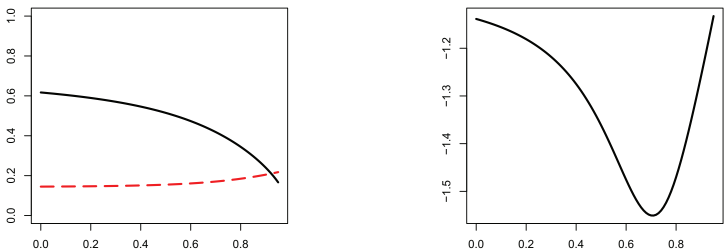
$$\frac{\rho_0}{\rho_0+\rho}\frac{\rho_{\tau_y}}{\rho}-\frac{\tau_0+\tau_y}{\tau_0+\tau_y+\tau}\frac{\tau_{\tau_y}}{\tau}>\frac{1}{2\tau_p}-\frac{1}{\tau_0+\tau_y+\tau} \tag{26}$$

where $\tau_{\tau_y}=\frac{\partial\tau(\tau_y)}{\partial\tau_y}$ and $\rho_{\tau_y}=\frac{\partial\rho(\tau_y)}{\partial\tau_y}$.

Efficiency responds to transparency as before, where condition (25) is the analog to condition (20) in Theorem 1. Note that greater disclosure (higher τ_y) has the same effect as lower prior uncertainty about fundamentals (higher τ_0) with respect to both the investor's objective function (23) as well as the impact of transparency on efficiency. Taken together, this establishes that our main result relating transparency and efficiency is robust to the introduction of public disclosures.

Moreover, (26) characterizes how increasing disclosure affects efficiency, in the absence of any concurrent change in transparency. The terms to the left of the inequality reflect how higher disclosure affects endogenous learning about fundamentals and other traders (these terms mirror the corresponding terms in (25)). Greater disclosure "crowds in" information acquisition about others, which is reflected by $\rho_{\tau_y}>0$, but "crowds out" private learning about fundamentals, which implies $\tau_{\tau_y}<0$. Both effects tend to increase the likelihood that efficiency falls, and are stronger when investors' private information is relatively imprecise (i.e., ρ and τ are relatively small). The terms to the right of the inequality reflect the direct effect of higher disclosure. All else equal, a higher value of τ_y implies that the first term is larger, while the second term is smaller, making it less likely that efficiency decreases with disclosure. The overall effect of disclosure on efficiency depends on the relative magnitude of the direct benefit of providing more information and each investor's endogenous response to this provision.

Figure 3 illustrates the impact of public disclosure on both the information acquired by investors and informational efficiency. As discussed above, higher disclosure "crowds in" learning about others (dashed line) but "crowds out" learning about fundamentals (solid line). The resultant effect on efficiency is nonmonotonic. When public disclosure is relatively low, the indirect effect dominates and efficiency falls with disclosure. However, once the public signal is sufficiently informative, the direct effect of disclosure dominates, and efficiency begins to increase with higher disclosure. This is true even though investors choose to acquire less private information about fundamentals—the public disclosure is sufficiently informative to offset this decline.



(a) $\frac{\tau}{\tau_0+\tau}$ (solid), $\frac{\rho}{\rho_0+\rho}$ (dashed) versus $\frac{\tau_y}{\tau_0+\tau_y}$ (b) Efficiency $\mathcal{E}$ versus $\frac{\tau_y}{\tau_0+\tau_y}$

Figure 3
Optimal precisions and efficiency as a function of disclosure τ_y
The figure plots optimal precision choices for fundamental information (i.e., $\frac{\tau}{\tau_0+\tau}$, solid) and information about others (i.e., $\frac{\rho}{\rho_0+\rho}$, dashed) and efficiency as a function of fundamental transparency $\frac{\tau_y}{\tau_0+\tau_y}$. Other parameter values are set to $\tau_0=\rho_0=1$ and $h=g=0.5$, $m=4$ and $n=1$, where the cost function is given by Equation (21).

6. Conclusions

When investors "agree to disagree" about the interpretation of public signals, we find that they have incentives to learn about both asset fundamentals and the beliefs of others. We characterize the endogenous information acquisition of investors in such a setting and show that learning along these two dimensions is complementary. Furthermore, we demonstrate that this complementarity can have important implications for regulatory policies that affect the information environment. We characterize conditions under which increasing fundamental transparency (i.e., making fundamental information easier to access) can, counterintuitively, make prices less informative about fundamentals. Complementarity implies that transparency increases acquisition of both types of information; if, in response, investors choose to learn relatively more about other investors, informational efficiency falls. We then analyze the effect of public disclosures of fundamental information. We find that public information crowds out private learning about fundamentals, but can crowd in private learning about other investors. As a result, the informational efficiency of all public information (i.e., accounting for prices as well as public disclosure) may fall as disclosure increases.

The economic relevance of the mechanism we highlight relies on the ability of some investors to learn about the behavior of other traders. The growing literature on high frequency trading (e.g., Brogaard et al. 2014; Hirschey 2017) suggests that the ability of some investors to anticipate the trading behavior of other investors has become increasingly important over the last several years. Our model predicts that as investors invest more in learning about other traders, prices become less informative. Since the complementarity in learning is driven by speculative incentives, the effects we describe are more pronounced around public announcements (e.g., earnings reports, macroeconomic news). This is consistent with Weller (2017), who documents a negative relation between price informativeness and algorithmic trading leading up to earnings announcements and other scheduled disclosures.

The importance of our mechanism is likely to differ across assets and over time. Since the speculative motive for trade is likely to be higher for assets in which investors disagree more, we expect our mechanism to be more relevant for stocks with higher analyst forecast dispersion (e.g., Diether et al. 2002; Banerjee 2011) and higher abnormal volume following public announcements (e.g., Kandel and Pearson 1995; Banerjee and Kremer 2010). Furthermore, recall that an increase in transparency is more likely to decrease efficiency when fundamental transparency is already high. As such, the effect is likely to be more prevalent in well-developed markets, where fundamental information is relatively easy to acquire, and become stronger over time, as such information becomes more widely available.[26]

From a policy perspective, these effects change the calculus on the value of improving access to financial data. If investors simply divert their resources to learning about the behavior of other traders, price efficiency can fall. To the extent that real decision-makers condition on the fundamental information contained in the price, this decrease in price efficiency can have detrimental effects on the real-side of the economy as well. This is especially true in light of the estimated cost of these regulations (see, for instance, Iliev 2010). However, our results should not be interpreted as a blanket recommendation for reducing transparency or disclosure. Instead, our analysis highlights the importance of understanding investors' incentives to acquire information, including information about the beliefs of other investors, when evaluating the impact of regulatory changes on financial markets.

Appendix A. Proofs of Main Results

Proof of Propositions 1 and 4. Proposition 1 is a special case in which $\tau_y = 0$. When investor l can condition on $\{f_l, a_l, Y\}$, her beliefs are given by

$$\mathbb{E}_l[F|f_l, Y] = e^{\frac{\tau_l f_l + \tau_y Y}{\tau_0 + \tau_l + \tau_y} + \frac{1}{2(\tau_0 + \tau_l + \tau_y)} - \frac{1}{2\tau_0}}, \tag{A1}$$

$$\mathbb{E}_l[A|a_l] = e^{\frac{\rho_l}{\rho_0 + \rho_l} a_l + \frac{1}{2(\rho_0 + \rho_l)} - \frac{1}{2\rho_0}}. \tag{A2}$$

Given the unconditional distributions of $\{f_l, Y\}$, we have

$$\frac{\tau_l f_l + \tau_y Y}{\tau_0 + \tau_l + \tau_y} \sim \mathcal{N}\left(0, \frac{1}{\tau_0} \frac{\tau_y + \tau_l}{\tau_0 + \tau_y + \tau_l}.\right) \tag{A3}$$

[26] This provides a potential explanation for the empirical evidence of Bai et al. (2016), who find that price informativeness for the full sample of CRSP stocks has declined since the 1960s (see footnote 2 of their paper).

Moreover, given that L investors exhibit differences of opinions, investor l's beliefs about P_1 is that $\log(P_1)=BY+W$ for some $W\sim\mathcal{N}(m_W,\frac{1}{\tau_W})$ independent of $\{f_l,a_l,Y\}$. Note that

$$\frac{\rho_l}{\rho_0+\rho_l}a_l\sim\mathcal{N}\left(0,\frac{1}{\rho_0}-\frac{1}{\rho_0+\rho_l}\right) \tag{A4}$$

$$\frac{\tau_l f_l+\tau_y Y}{\tau_0+\tau_l+\tau_y}+BY\sim\mathcal{N}\left(0,\frac{(1+B)^2}{\tau_0}+\frac{B^2}{\tau_y}-\frac{1}{\tau_0+\tau_y+\tau_l}\right). \tag{A5}$$

This implies that

$$\mathbb{E}_{l,0}[P_1E_l[F|f_l]E_l[A|a_l]]$$

$$=\mathbb{E}_{l,0}\left[P_1\times e^{\frac{\tau_l f_l+\tau_y Y}{\tau_0+\tau_l+\tau_y}+\frac{1}{2(\tau_0+\tau_l+\tau_y)}-\frac{1}{2\tau_0}}\times e^{\frac{\rho_l}{\rho_0+\rho_l}a_l+\frac{1}{2(\rho_0+\rho_l)}-\frac{1}{2\rho_0}}\right] \tag{A6}$$

$$=e^{m_W+\frac{1}{2\tau_W}-\frac{1}{2\tau_0}-\frac{1}{2\rho_0}}\mathbb{E}_{l,0}\left[e^{\frac{\tau_l f_l+\tau_y Y}{\tau_0+\tau_l+\tau_y}+BY+\frac{1}{2(\tau_0+\tau_l+\tau_y)}+\frac{\rho_l}{\rho_0+\rho_l}a_l+\frac{1}{2(\rho_0+\rho_l)}}\right] \tag{A7}$$

$$=e^{m_W+\frac{1}{2\tau_W}+\frac{1}{2}\left(\frac{(1+B)^2}{\tau_0}+\frac{B^2}{\tau_y}\right)}, \tag{A8}$$

which does not depend on information choices τ_l or ρ_l. This implies that $V_{l,0}$ can be expressed as

$$V_{l,0}=\mathbb{E}_{l,0}\left[x_{l,2}(\phi-P_2)-\tfrac{\lambda}{2}x_{l,2}^2+x_{l,1}(P_2-P_1)-\tfrac{\lambda}{2}x_{l,1}^2\right] \tag{A9}$$

$$=\tfrac{1}{2\lambda}\left(\bar{V}+\mathbb{E}_{l,0}\left[(\mathbb{E}_l[F|f_l,Y])^2\times(\mathbb{E}_l[A|a_l])^2\right]\right) \tag{A10}$$

$$=\tfrac{1}{2\lambda}\left(\bar{V}+e^{\frac{1}{\tau_0}-\frac{1}{\tau_0+\tau_l+\tau_y}+\frac{1}{\rho_0}-\frac{1}{\rho_0+\rho_l}}\right), \tag{A11}$$

such that $\bar{V}$ does not depend on τ_l or ρ_l. Letting $\tilde{V}_{l,0}\equiv e^{\frac{1}{\tau_0}-\frac{1}{\tau_0+\tau_l+\tau_y}+\frac{1}{\rho_0}-\frac{1}{\rho_0+\rho_l}}$, we can characterize the choice of optimal precisions with the following first-order (FOC) conditions:

$$\tilde{V}_{l,0}=\frac{\partial C}{\partial\tau_l}\times(\tau_0+\tau_y+\tau_l)^2,\quad \tilde{V}_{l,0}=\frac{\partial C}{\partial\rho_l}\times(\rho_0+\rho_l)^2. \tag{A12}$$

The second-order (SOC) conditions for a maximum are given by

$$\tilde{V}_{l,0}\frac{1-2(\tau_0+\tau_y+\tau_l)}{(\tau_0+\tau_y+\tau_l)^4}-\frac{\partial^2 C}{\partial\tau_l^2}<0 \tag{A13}$$

$$\tilde{V}_{l,0}\frac{1-2(\rho_0+\rho_l)}{(\rho_0+\rho_l)^4}-\frac{\partial^2 C}{\partial\rho_l^2}<0 \tag{A14}$$

$$\left(\tilde{V}_{l,0}\tfrac{1-2(\tau_0+\tau_y+\tau_l)}{(\tau_0+\tau_y+\tau_l)^4}-\tfrac{\partial^2 C}{\partial\tau_l^2}\right)\left(\tilde{V}_{l,0}\tfrac{1-2(\rho_0+\rho_l)}{(\rho_0+\rho_l)^4}-\tfrac{\partial^2 C}{\partial\rho_l^2}\right)<\left(\tilde{V}_{l,0}\tfrac{1}{(\rho_0+\rho_l)^2(\tau_0+\tau_y+\tau_l)^2}-\tfrac{\partial^2 C}{\partial\rho_l\partial\tau_l}\right)^2. \tag{A15}$$

Since the cost function is convex (i.e., $\frac{\partial^2 C}{\partial\tau_l^2}>0$, $\frac{\partial^2 C}{\partial\rho_l^2}>0$) and separable (i.e., $\frac{\partial^2 C}{\partial\rho_l\partial\tau_l}=0$), it is sufficient to ensure

$$\frac{1-2(\tau_0+\tau_y+\tau_l)}{(\tau_0+\tau_y+\tau_l)^4}<0,\quad \frac{1-2(\rho_0+\rho_l)}{(\rho_0+\rho_l)^4}<0,\quad\text{and} \tag{A16}$$

$$\left(\frac{1-2(\rho_0+\rho_l)}{(\rho_0+\rho_l)^4}\right)\left(\frac{1-2(\tau_0+\tau_y+\tau_l)}{(\tau_0+\tau_y+\tau_l)^4}\right)>\left(\frac{1}{(\rho_0+\rho_l)^2(\tau_0+\tau_y+\tau_l)^2}\right)^2. \tag{A17}$$

It is easy to verify that $\tau_0,\rho_0>1$ are sufficient conditions for the above to hold and hence sufficient for the existence and uniqueness of optimal precisions.

Moreover, learning about both dimensions are valuable and exhibits complementarity:

$$\frac{\partial}{\partial \tau_i} V_{L,0} > 0, \quad \frac{\partial}{\partial \rho_i} V_{L,0} > 0, \quad \frac{\partial^2}{\partial \tau_i \partial \rho_i} V_{L,0} > 0.$$

The objective function in (18) exhibits complementarity in $\{\tau_l, h\}$, $\{\rho_l, h\}$, and $\{\tau_l, \rho_l\}$. Therefore, theorem 4.2.2 in Topkis (2011) on comparative statics of equilibria in supermodular games can be applied to show that optimal precisions τ_l, ρ_l increase in h. ■

Proof of Proposition 2 and 5. Proposition 2 is a special case in which $\tau_y = 0$. Let $\mu_f = \mathbb{E}[f|P_1, Y]$ and $1/\tau_f = \mathrm{var}[f|P_1, Y]$ denote the observer's conditional mean and variance about f, given the price P_1 and public disclosure Y. In the symmetric equilibrium, investor l's beliefs are given by (A1) and (A2), and so the price is given by

$$P_1 = \int_{l \in L} (\mathbb{E}_l[A|a_l] \times \mathbb{E}_l[F|f_l]) dl \tag{A18}$$

$$= \int_{l \in L} e^{\frac{\tau_l f_l + \tau_y Y}{\tau_0 + \tau_l + \tau_y} + \frac{1}{2(\tau_0 + \tau_l + \tau_y)} - \frac{1}{\tau_0} + \frac{\rho_l}{\rho_0 + \rho_l} a_l + \frac{1}{2(\rho_0 + \rho_l)} - \frac{1}{2\rho_0}} dl \tag{A19}$$

$$\equiv e^{p + \bar{p}}, \tag{A20}$$

where $\bar{p}$ is a constant, and $p = \frac{\tau f + \tau_y Y}{\tau_0 + \tau + \tau_y} + \frac{\rho}{\rho_0 + \rho} A$. Conditioning on P_1 is informationally equivalent to conditioning on p, and so

$$\mu_f = \frac{\tau_p p + \tau_y Y}{\tau_0 + \tau_p + \tau_y} \sim \mathcal{N}\left(0, \frac{\tau_p + \tau_y}{\tau_0(\tau_0 + \tau_p + \tau_y)}\right) \tag{A21}$$

$$\tau_f = \tau_0 + \tau_y + \tau_p, \quad \text{where} \tag{A22}$$

$$\tau_p = \rho_0 \left(\frac{\tau}{\tau_0 + \tau + \tau_y} \frac{\rho_0 + \rho}{\rho} \right)^2. \tag{A23}$$

Then price efficiency can be expressed as

$$\mathcal{E} = -\mathbb{E}_0 \left[(\phi - \mathbb{E}[\phi|P_1, Y])^2 \right] \tag{A24}$$

$$= -\left(\tfrac{1}{\tau_u} + \mathbb{E}_0[\mathrm{var}(F|P_1, Y)] \right) \tag{A25}$$

$$= -\left(\tfrac{1}{\tau_u} + \mathbb{E}_0 \left[(e^{\frac{1}{\tau_f}} - 1) e^{2\mu_f + \frac{1}{\tau_f} - \frac{1}{\tau_0}} \right] \right) \tag{A26}$$

$$= -\left(\tfrac{1}{\tau_u} + (e^{\frac{1}{\tau_f}} - 1) e^{\frac{1}{\tau_f} - \frac{1}{\tau_0}} \mathbb{E}_0 \left[e^{2\mu_f} \right] \right) \tag{A27}$$

which implies that efficiency is increasing in

$$\tilde{\mathcal{E}} \equiv \tau_0 + \tau_y + \rho_0 \left(\frac{\tau}{\tau_0 + \tau + \tau_y} \frac{\rho_0 + \rho}{\rho} \right)^2,$$

giving us the result. ■

Proof of Theorem 1 and 2. The result follows from differentiating the expression for $\tilde{\mathcal{E}}$ with respect to transparency h for Theorems 1 and 2, and with respect to τ_y for Theorem 2. ■

Proof of Proposition 3. Given the cost function, note that

$$\frac{\partial C}{\partial \tau_l} = e^{\frac{1}{\tau_0}+\frac{1}{\rho_0}}\left(\frac{1}{h}\frac{\tau_0}{(\tau_l+\tau_0)^2}\left(\frac{\tau_l}{\tau_0+\tau_l}\right)^m\right), \qquad \frac{\partial^2 C}{\partial \tau_l^2} = \frac{m\tau_0 - 2\tau_l}{\tau_l(\tau_0+\tau_l)} \times \frac{\partial C}{\partial \tau_l}, \tag{A28}$$

$$\frac{\partial V_{l,0}}{\partial \tau_l} = \tilde{V}_{l,0}\frac{1}{(\tau_0+\tau_l)^2}, \qquad \frac{\partial^2 V_{l,0}}{\partial \tau_l^2} = \tilde{V}_{l,0}\frac{1-2(\tau_0+\tau_l)}{(\tau_0+\tau_l)^4} \tag{A29}$$

and similarly for ρ_l. The first-order conditions $\frac{\partial V_{l,0}}{\partial \tau_l} = \frac{\partial C}{\partial \tau_l}$ and $\frac{\partial V_{l,0}}{\partial \rho_l} = \frac{\partial C}{\partial \rho_l}$, and the second-order conditions

$$\frac{\partial^2 V_{l,0}}{\partial \tau_l^2} - \frac{\partial^2 C}{\partial \tau_l^2} < 0, \quad \frac{\partial^2 V_{l,0}}{\partial \rho_l^2} - \frac{\partial^2 C}{\partial \rho_l^2} < 0, \quad \left(\frac{\partial^2 V_{l,0}}{\partial \tau_l^2} - \frac{\partial^2 C}{\partial \tau_l^2}\right)\left(\frac{\partial^2 V_{l,0}}{\partial \rho_l^2} - \frac{\partial^2 C}{\partial \rho_l^2}\right) > \left(\frac{\partial^2 V_{l,0}}{\partial \tau_l \partial \rho_l}\right)^2$$

hold for each investor l. The FOC imply that

$$e^{-\frac{1}{\tau_0+\tau}-\frac{1}{\rho_0+\rho}} = \frac{\tau_0}{h}\left(\frac{\tau}{\tau_0+\tau}\right)^m, \qquad e^{-\frac{1}{\tau_0+\tau}-\frac{1}{\rho_0+\rho}} = \frac{\rho_0}{g}\left(\frac{\rho}{\rho_0+\rho}\right)^n. \tag{A30}$$

Differentiating these conditions with respect to h and simplifying gives

$$\frac{\tau_h}{(\tau_0+\tau)^2} + \frac{\rho_h}{(\rho_0+\rho)^2} = -\frac{1}{h} + \left(\frac{m\tau_0}{\tau(\tau_0+\tau)}\right)\tau_h \tag{A31}$$

$$\frac{\tau_h}{(\tau_0+\tau)^2} + \frac{\rho_h}{(\rho_0+\rho)^2} = \left(\frac{n\rho_0}{\rho(\rho_0+\rho)}\right)\rho_h. \tag{A32}$$

Let $x = \frac{\tau_h}{(\tau_0+\tau)^2}$, $y = \frac{\rho_h}{(\rho_0+\rho)^2}$, $A = \frac{m\tau_0(\tau_0+\tau)}{\tau}$, and $B = \frac{n\rho_0(\rho_0+\rho)}{\rho}$. Then, the above system can be expressed as

$$x+y = -\frac{1}{h} + Ax, \quad x+y = By,$$

and so the solutions are given by

$$x = \frac{B-1}{h(AB-A-B)}, \quad y = \frac{1}{h(AB-A-B)}.$$

Moreover, by substituting the FOC into the SOC, one can show that the required SOC conditions are equivalent to $A>1$, $B>1$ and $AB > A+B$. In turn, this implies that $x, y > 0$ as expected. Given the expressions for A and B, assuming $(m\tau_0 - 1)(n\rho_0 - 1) > 1$ is sufficient to ensure the above. Recall that efficiency is decreasing in h if

$$\frac{\tau_0}{\tau}\frac{\tau_h}{\tau_0+\tau} < \frac{\rho_0}{\rho}\frac{\rho_h}{\rho_0+\rho} \quad \Leftrightarrow \quad \frac{xA}{m} < \frac{yB}{n} \quad \Leftrightarrow \quad A < \frac{m}{n}\frac{B}{B-1}. \tag{A33}$$

Since we know $A(B-1) > B$ from the SOC, for the above condition to hold, we must have $m > n$. Moreover, note that

$$\frac{\partial A}{\partial h} = \frac{\partial A}{\partial \tau}\tau_h < 0, \quad \frac{\partial}{\partial h}\left(\frac{B}{B-1}\right) = \frac{\partial}{\partial \rho}\left(\frac{B}{B-1}\right)\rho_h = \frac{n\rho_0^2}{(n\rho_0^2 + \rho(n\rho_0 - 1))^2}\rho_h > 0,$$

and

$$\lim_{h\to 0} A = \infty, \quad \lim_{h\to\infty} A = m\tau_0,$$

and for a fixed g,

$$\lim_{h\to 0} B = \frac{n\rho_0(\rho_0+\underline{\rho})}{\underline{\rho}}, \quad \lim_{h\to\infty} B = \frac{n\rho_0(\rho_0+\bar{\rho})}{\bar{\rho}},$$

where $\underline{\rho} \equiv \lim_{h\to 0} \rho(h)$ and $\bar{\rho} \equiv \lim_{h\to\infty} \rho(h)$ are the optimal choice of ρ for minimal and maximal fundamental transparency, respectively. Note that $\underline{\rho}$ and $\bar{\rho}$ solve

$$e^{\frac{1}{\rho_0} - \frac{1}{\rho_0 + \underline{\rho}}} = e^{\frac{1}{\tau_0} + \frac{1}{\rho_0}} \frac{\rho_0}{g} \left(\frac{\underline{\rho}}{\rho_0 + \underline{\rho}} \right)^n \tag{A34}$$

$$e^{\frac{1}{\tau_0} + \frac{1}{\rho_0} - \frac{1}{\rho_0 + \bar{\rho}}} = e^{\frac{1}{\tau_0} + \frac{1}{\rho_0}} \frac{\rho_0}{g} \left(\frac{\bar{\rho}}{\rho_0 + \bar{\rho}} \right)^n \tag{A35}$$

and so $0 \leq \underline{\rho} \leq \bar{\rho} \leq \infty$. This implies that efficiency cannot decrease with transparency if

$$m\tau_0 > \frac{m}{n} \frac{B}{B-1} = \frac{m}{n} \left(1 + \frac{\rho}{n\rho_0^2 + \rho(n\rho_0 - 1)} \right)$$

for all ρ, or equivalently,

$$\tau_0 > \frac{1}{n} \left(1 + \frac{\bar{\rho}}{n\rho_0^2 + \bar{\rho}(n\rho_0 - 1)} \right).$$

On the other hand, if

$$\tau_0 < \frac{1}{n} \left(1 + \frac{\bar{\rho}}{n\rho_0^2 + \bar{\rho}(n\rho_0 - 1)} \right),$$

then efficiency increases and then decreases in transparency. The latter condition can be expressed as

$$\bar{\rho} > \frac{\rho_0^2 (n\tau_0 - 1)}{\rho_0 + \tau_0 - n\rho_0\tau_0}$$

From (A35), note that $\bar{\rho}$ does not depend on $\frac{1}{\tau_0}$, and so the above condition can be ensured by setting g to be sufficiently high. Let $\bar{g}$ be the value of g in (A35) such that $\bar{\rho} = \frac{\rho_0^2 (n\tau_0 - 1)}{\rho_0 + \tau_0 - n\rho_0\tau_0}$, and we have the result. ■

Appendix B. Learning from Prices

In this section, we analyze a version of the model in which L investors update their beliefs at date 1 using the information in prices; that is, they share common priors about the joint distribution of private signals. Given this modification, we ensure that prices are not fully revealing by assuming there exists a continuum of liquidity traders at date one whose net supply of the asset is given by

$$Z_1 = \frac{1}{\lambda} \left(e^{-z} - 1 \right) P_1, \text{ where } z \sim N\left(0, \frac{1}{\omega_0}\right). \tag{A36}$$

All other assumptions (preferences, beliefs, and signal structures) follow those used in the benchmark model. Analogous calculations imply that the date two price is given by $P_2 = AF$, and optimal demand by l investors is

$$x_{l,1} = \frac{1}{\lambda} (\mathbb{E}_l [P_2 | f_l, a_l, P_1] - P_1), \tag{A37}$$

so that market clearing implies

$$\int_{l \in L} x_{l,1} dl = Z_1 \tag{A38}$$

$$\Rightarrow P_1 = e^z \int_{l \in L} \mathbb{E}_l [P_2 | f_l, a_l, P_1] dl. \tag{A39}$$

As such, the date 1 price provides a noisy signal of the average beliefs of l investors about the date two price. Note the above setting is analogous to the one in Sockin and Xiong (2015), but the price is a signal about two underlying shocks (A and F). The following result characterizes sufficient conditions for the existence of a noisy REE at date 1.

Proposition 6. Suppose $\omega_0 \leq \min\{\rho_0, \tau_0\}$. If the date 0 optimal choice of precisions for L investors is $\{\tau, \rho\}$, then there exists a unique equilibrium where the price at date 1 is given by

$$P = \exp\left\{\alpha(\theta_1 f + \theta_2 a + z) + \tfrac{1}{2}\Sigma_p\right\}, \tag{A40}$$

where

$$\alpha = \left(1 + \frac{\omega_0(\theta_1(\rho+\rho_0)+\theta_2(\tau+\tau_0))}{\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)}\right), \text{ and} \tag{A41}$$

$$\Sigma_p = \frac{\theta_1^2}{\tau} + \frac{\theta_2^2}{\rho} - \frac{1}{\tau_0} - \frac{1}{\rho_0} + \frac{(\theta_1-\theta_2)^2\omega_0+\rho+\rho_0+\tau+\tau_0}{\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)}, \tag{A42}$$

and $\theta_1, \theta_2 \in [0,1]$ are solutions to the following system:

$$\theta_1 = \frac{\tau(\theta_2(\theta_2-\theta_1)\omega_0+\rho+\rho_0)}{\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)}, \tag{A43}$$

$$\theta_2 = \frac{\rho(\theta_1(\theta_1-\theta_2)\omega_0+\tau+\tau_0)}{\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)}. \tag{A44}$$

Given the above characterization, one can derive the date zero optimal information acquisition decision for investor l in a symmetric equilibrium. Specifically, given the choice of precisions $\{\tau, \rho\}$ of other investors, the optimal choice of precisions $\{\tau_l, \rho_l\}$ for investor l must maximize her expected gains from trade:

$$V_{l,0} = \max_{\tau_l,\rho_l} \mathbb{E}_0\left[V_{l,1}\right] \tag{A45}$$

$$= \max_{\tau_l,\rho_l} \frac{1}{2\lambda}\mathbb{E}_0\left[\left(e^F - P_2\right)^2 + \left(\mathbb{E}\left[P_2 \middle| f_l, a_l, P_1\right] - P_1\right)^2\right] \tag{A46}$$

$$= \max_{\tau_l,\rho_l} \frac{1}{2\lambda}\mathbb{E}_0\left[\left(e^F - P_2\right)^2 + P_1^2 + \left(\mathbb{E}\left[P_2 \middle| f_l, a_l, P_1\right]\right)^2 - 2P_1\mathbb{E}\left[P_2 \middle| f_l, a_l, P_1\right]\right] \tag{A47}$$

$$= \max_{\tau_l,\rho_l} \frac{1}{2\lambda}\left(\bar{V} + V(\tau_l, \rho_l; \tau, \rho)\right) \tag{A48}$$

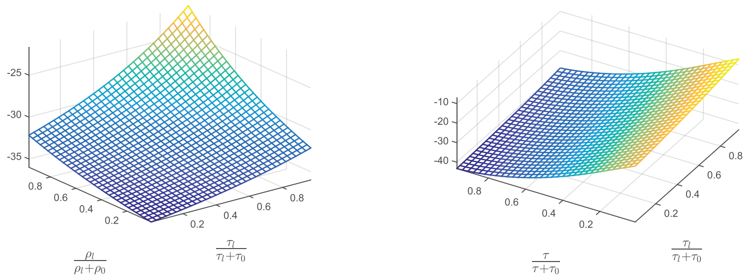
where, as before, $\bar{V}$ does not depend on τ_l or ρ_l, and $V(\tau_l, \rho_l; \tau, \rho)$ is given by

$$V(\tau_l, \rho_l; \tau, \rho) = \mathbb{E}_0\left[\left(\mathbb{E}\left[P_2 \middle| f_l, a_l, P_1\right]\right)^2 - 2P_1\mathbb{E}\left[P_2 \middle| f_l, a_l, P_1\right]\right].$$

Unlike in the benchmark case, in this setting, investor l's value from acquiring information now depends on the acquisition choices of other investors. While analytically characterizing complementarity in learning is not feasible in this setting, we can numerically characterize the behavior of the function $V(\cdot)$. Figure B1 provides an illustrative example. Panel (a) establishes that, even though investors learn from prices in this setting, for an investor learning about F and A are complementary. Specifically, the benefit from increasing ρ_i is higher when τ_i is higher and vice versa, that is,

$$\frac{\partial^2 V_{l,0}}{\partial \tau_l \partial \rho_l} > 0. \tag{A49}$$

On the other hand, consistent with our intuition from noisy rational expectations equilibria (e.g., Grossman and Stiglitz 1980), panel (b) suggests that learning about fundamentals exhibits strategic



(a) $V(\tau_i, \rho_i; \tau, \rho)$ vs $\frac{\tau_l}{\tau_l+\tau_0}$ and $\frac{\rho_l}{\rho_l+\rho_0}$ (b) $V(\tau_i, \rho_i; \tau, \rho)$ vs $\frac{\tau_l}{\tau_l+\tau_0}$ and $\frac{\tau}{\tau+\tau_0}$

Figure B1
Plot of $V(\tau_l, \rho_l; \tau, \rho)$
Plot of $V(\tau_l, \rho_l; \tau, \rho)$ as a function of (a) $\frac{\tau_l}{\tau_l+\tau_0}$ and $\frac{\rho_l}{\rho_l+\rho_0}$ and (b) $\frac{\tau_l}{\tau_l+\tau_0}$ and $\frac{\tau}{\tau+\tau_0}$. Unless noted otherwise, parameters are set to $\tau_0 = \rho_0 = \omega_0 = 1 = \tau = \rho$.

substitutability. In particular, the marginal benefit from increasing τ_i is lower when τ is higher, that is,

$$\frac{\partial^2 V_{l,0}}{\partial \tau_l \partial \tau} < 0. \tag{A50}$$

These results highlight the key difference between the notion of complementarity in learning in our model versus the notion of strategic complementarity that is widely studied in the literature. In our model, learning about fundamentals and other investors exhibits complementarity because learning more along one dimension increases the value of learning more about the other, for each investor. However, learning about fundamentals is also a *strategic substitute*, since learning more about fundamentals is less valuable when other investors also learn about fundamentals.

Given a cost function $C(\tau_l, \rho_l, h)$, one can characterize the optimal choice of precisions for investor l as

$$\tau_l^*(\tau, \rho, h), \rho_l^*(\tau, \rho, h) = \arg\max_{\tau_l, \rho_l} V(\tau_l, \rho_l; \tau, \rho) - C(\tau_l, \rho_l, h). \tag{A51}$$

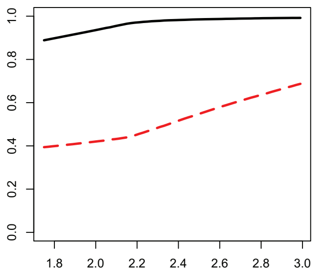
Finally, the optimal precision choices in the symmetric, information acquisition equilibrium are given by the fixed point solutions to the following system:

$$\tau = \tau_l^*(\tau, \rho, h) \text{ and } \rho = \rho_l^*(\tau, \rho, h). \tag{A52}$$

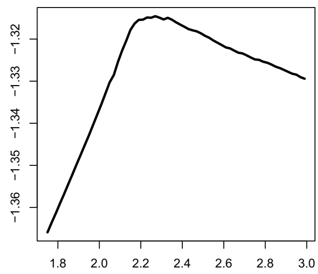
Again, analytically characterizing the equilibrium choices of precision is not feasible in our setting. Instead, we explore the equilibrium and the resultant impact on informational efficiency numerically.

Figure B2 presents a numerical illustration of our results. To facilitate comparisons to our benchmark model results, the specification for the cost function is identical to the one in the paper (see Equation (21)), and parameter values are chosen to match those in Figure 2 of the paper when appropriate. Like in our benchmark model, complementarity in learning implies that increasing fundamental transparency increases the equilibrium learning about fundamentals and about others, even when investors are also updating their beliefs using the information in prices. For initial levels of transparency, learning about fundamentals increases (relatively) more quickly than learning about fundamentals and, consequently, efficiency increases. However, when transparency is sufficiently high, the rate of learning about others is higher than the rate of learning about fundamentals, and efficiency begins to fall.

The quantitative effects of an increase in transparency are evidently different from the benchmark model in the paper, since investors now update their beliefs using the information in the price.



(a) $\frac{\tau}{\tau_0+\tau}$ (solid) and $\frac{\rho}{\rho_0+\rho}$ (dashed) versus h



(b) Efficiency $\mathcal{E}$ versus h

Figure B2
Equilibrium precisions and efficiency vs transparency
The figure plots optimal precision choices for fundamental information (i.e., $\frac{\tau}{\tau_0+\tau}$, solid) and information about others (i.e., $\frac{\rho}{\rho_0+\rho}$ dashed) and efficiency as a function of fundamental transparency h. Other parameter values are set to $\tau_0=\rho_0=1$, $\omega_0=0.9$, $g=0.9$, $m=4$, and $n=1$, where the cost function is given by Equation (21) in the paper.

However, the numerical analysis in this section suggests that our results are qualitatively robust to allowing investors to learn from prices.

Proof of Proposition 6. Suppose the price at date 1 is equivalent to a signal $s_p=\theta_1 f+\theta_2 a+z$, where $z\sim N\left(0,\frac{1}{\omega_0}\right)$. Let

$$X=\begin{pmatrix} f \\ a \end{pmatrix}\sim N\left(\begin{pmatrix} 0 \\ 0 \end{pmatrix},\begin{pmatrix} \frac{1}{\tau_0} & 0 \\ 0 & \frac{1}{\rho_0} \end{pmatrix}\right)\equiv N(0,\Sigma_X) \tag{A53}$$

$$S=\begin{pmatrix} f_i \\ a_i \\ s_p \end{pmatrix}\sim N\left(\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix},\begin{pmatrix} \frac{1}{\tau_0}+\frac{1}{\tau_i} & 0 & \frac{\theta_1}{\tau_0} \\ 0 & \frac{1}{\rho_0}+\frac{1}{\rho_i} & \frac{\theta_2}{\rho_0} \\ \frac{\theta_1}{\tau_0} & \frac{\theta_2}{\rho_0} & \frac{\theta_1^2}{\tau_0}+\frac{\theta_2^2}{\rho_0}+\frac{1}{\omega_0} \end{pmatrix}\right)\equiv N(0,\Sigma_S) \tag{A54}$$

$$\Sigma_{XS}=\begin{pmatrix} \frac{1}{\tau_0} & 0 & \frac{\theta_1}{\tau_0} \\ 0 & \frac{1}{\rho_0} & \frac{\theta_2}{\rho_0} \end{pmatrix} \tag{A55}$$

In this case,

$$X|S\sim N\left(\Sigma_{XS}\Sigma_S^{-1}S,\ \Sigma_X-\Sigma_{XS}\Sigma_S^{-1}\Sigma_{SX}\right) \tag{A56}$$

and so

$$\mathbb{E}\left[f+a|f_i,a_i,s_p\right]=\frac{\rho a_i(\theta_1(\theta_1-\theta_2)\omega_0+\tau+\tau_0)+\tau f_i(\theta_2(\theta_2-\theta_1)\omega_0+\rho+\rho_0)+\omega_0 s_p(\theta_1(\rho+\rho_0)+\theta_2(\tau+\tau_0))}{\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)}$$

$$\equiv\kappa_f f_i+\kappa_a a_i+\kappa_p s_p$$

$$\text{var}\left[f+a|f_i,a_i,s_p\right]=\frac{(\theta_1-\theta_2)^2\omega_0+\rho+\rho_0+\tau+\tau_0}{\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)}\equiv\Sigma$$

$$P_1 = e^z \int_i \mathbb{E}\left[AF \middle| f_i, a_i s_p\right] di \tag{A57}$$

$$= e^{z - \frac{1}{2\tau_0} - \frac{1}{2\rho_0}} \int_i e^{\kappa_f f_i + \kappa_a a_i + \kappa_p s_p + \frac{1}{2}\Sigma} di \tag{A58}$$

$$= \exp\left\{ z + \kappa_f f + \kappa_a a + \kappa_p s_p + \frac{1}{2}\left(\frac{\kappa_f^2}{\tau} + \frac{\kappa_a^2}{\rho} + \Sigma - \frac{1}{\tau_0} - \frac{1}{\rho_0} \right) \right\} \tag{A59}$$

$$= \exp\left\{ z\left(1+\kappa_p\right) + \left(\kappa_f + \kappa_p\theta_1\right) f + \left(\kappa_a + \kappa_p\theta_2\right) a + \frac{1}{2}\left(\frac{\kappa_f^2}{\tau} + \frac{\kappa_a^2}{\rho} + \Sigma - \frac{1}{\tau_0} - \frac{1}{\rho_0} \right) \right\}, \tag{A60}$$

This implies

$$\theta_1 = \frac{\kappa_f + \kappa_p\theta_1}{1+\kappa_p},\ \theta_2 = \frac{\kappa_a + \kappa_p\theta_2}{1+\kappa_p} \tag{A61}$$

$$\Rightarrow \theta_1 = \kappa_f, \quad \theta_2 = \kappa_a. \tag{A62}$$

This implies θ_1 and θ_2 solve the system:

$$\theta_1 = \frac{\tau(\theta_2(\theta_2-\theta_1)\omega_0+\rho+\rho_0)}{\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)} \equiv g_1(\theta_1,\theta_2), \tag{A63}$$

$$\theta_2 = \frac{\rho(\theta_1(\theta_1-\theta_2)\omega_0+\tau+\tau_0)}{\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)} \equiv g_2(\theta_1,\theta_2) \tag{A64}$$

and that $P_1 = \exp\left\{\left(1+\kappa_p\right)s_p + \frac{1}{2}\Sigma_p\right\}$, where $\Sigma_p = \frac{\kappa_f^2}{\tau} + \frac{\kappa_a^2}{\rho} + \Sigma - \frac{1}{\tau_0} - \frac{1}{\rho_0}$.

Next, note that for $\theta_1, \theta_2 \in [0,1]$,

$$g_1(0,\theta_2) = \frac{\tau\left(\theta_2^2\omega_0+\rho+\rho_0\right)}{\omega_0\left(\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)} \in [0,1] \tag{A65}$$

$$g_1(1,\theta_2) = \frac{\tau(\theta_2(\theta_2-1)\omega_0+\rho+\rho_0)}{\omega_0\left((\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)} \in [0,1] \tag{A66}$$

$$\frac{\partial}{\partial\theta_1} g_1 = -\frac{\tau\omega_0\left(\theta_2(\tau+\tau_0)\left(\theta_2^2\omega_0+\rho+\rho_0\right)+2\theta_1(\rho+\rho_0)\left(\theta_2^2\omega_0+\rho+\rho_0\right)-\theta_2\theta_1^2(\rho+\rho_0)\omega_0\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A67}$$

$$\leq -\frac{\tau\omega_0\left(\theta_2(\tau+\tau_0)\left(\theta_2^2\omega_0\right)+2\theta_1(\rho+\rho_0)\left(\theta_2^2\omega_0+\rho+\rho_0\right)+\theta_2(\rho+\rho_0)(\tau+\tau_0-\omega_0)\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A68}$$

$$< 0 \text{ since } \omega_0 \leq \tau_0 \tag{A69}$$

$$\frac{\partial g_1}{\partial\theta_2} = \frac{\theta_1\tau\omega_0\left(\omega_0\left(2\theta_2\theta_1(\rho+\rho_0)-\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)-(\rho+\rho_0)(\tau+\tau_0)\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A70}$$

$$= \frac{\theta_1\tau\omega_0\left(\omega_0\left(\theta_2^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)-(\rho_0+\rho)(\theta_2-\theta_1)^2\right)-(\rho+\rho_0)(\tau+\tau_0)\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A71}$$

$$= \frac{\theta_1\tau\omega_0\left(\omega_0\left((2\theta_2-\theta_1)\theta_1(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)-(\rho+\rho_0)(\tau+\tau_0)\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A72}$$

since $\omega_0 \le \tau_0$. Similarly,

$$g_2(\theta_1, 0) = \frac{\rho\left(\theta_1^2\omega_0+\tau+\tau_0\right)}{\omega_0\left(\theta_1^2(\rho+\rho_0)\right)+(\rho+\rho_0)(\tau+\tau_0)} \in [0,1] \tag{A73}$$

$$g_2(\theta_1, 1) = \frac{\rho(\theta_1(\theta_1-1)\omega_0+\tau+\tau_0)}{\omega_0\left(\theta_1^2(\rho+\rho_0)+(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)} \in [0,1] \tag{A74}$$

$$\frac{\partial}{\partial\theta_2} g_2 = -\frac{\rho\omega_0\left(\theta_1(\tau+\tau_0)\left(\rho+\rho_0-\theta_2^2\omega_0\right)+\theta_1^3(\rho+\rho_0)\omega_0+2\theta_2\theta_1^2(\tau+\tau_0)\omega_0+2\theta_2(\tau+\tau_0)^2\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A75}$$

$$\le -\frac{\rho\omega_0\left(\theta_1(\tau+\tau_0)(\rho+\rho_0-\omega_0)+\theta_1^3(\rho+\rho_0)\omega_0+2\theta_2\theta_1^2(\tau+\tau_0)\omega_0+2\theta_2(\tau+\tau_0)^2\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A76}$$

$$< 0 \qquad \text{since } \omega_0 \le \rho_0 \tag{A77}$$

$$\frac{\partial}{\partial\theta_1} g_2 = \frac{\theta_2\rho\omega_0\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+2\theta_2\theta_1(\tau+\tau_0)-\theta_2^2(\tau+\tau_0)\right)-(\rho+\rho_0)(\tau+\tau_0)\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A78}$$

$$= \frac{\theta_2\rho\omega_0\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_1^2(\tau_0+\tau)-(\tau_0+\tau)(\theta_1-\theta_2)^2\right)-(\rho+\rho_0)(\tau+\tau_0)\right)}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^2} \tag{A79}$$

$$\tag{A80}$$

Since $\frac{\partial}{\partial\theta_1} g_1 < 0$, we have for any $\theta_2 \in [0,1]$, there exists a unique solution $\theta_1 \in [0,1]$ to $\theta_1 = g_1(\theta_1, \theta_2) \equiv h(\theta_2)$. Moreover, note that

$$\Rightarrow \frac{\partial h}{\partial\theta_2} = \frac{\frac{\partial g_1}{\partial\theta_2}}{1-\frac{\partial g_1}{\partial\theta_1}}. \tag{A81}$$

Next, one can express $\theta_2 = g_2(h(\theta_2), \theta_2) = f(\theta_2)$. Therefore, it is sufficient to show that $\frac{\partial f}{\partial\theta_2} < 0$ to ensure existence and uniqueness.

$$\frac{\partial f}{\partial\theta_2} = \frac{\partial g_2}{\partial\theta_1}\frac{\partial h}{\partial\theta_2} + \frac{\partial g_2}{\partial\theta_2} = \frac{\frac{\partial g_2}{\partial\theta_1}\frac{\partial g_1}{\partial\theta_2}}{1-\frac{\partial g_1}{\partial\theta_1}} + \frac{\partial g_2}{\partial\theta_2} \tag{A82}$$

$$= \frac{\frac{\partial g_2}{\partial\theta_1}\frac{\partial g_1}{\partial\theta_2} - \frac{\partial g_2}{\partial\theta_2}\frac{\partial g_1}{\partial\theta_1} + \frac{\partial g_2}{\partial\theta_2}}{1-\frac{\partial g_1}{\partial\theta_1}}. \tag{A83}$$

The above implies $\frac{\partial g_1}{\partial\theta_1} < 0$ and $\frac{\partial g_2}{\partial\theta_2} < 0$, so it is sufficient to establish:

$$\frac{\partial g_2}{\partial\theta_1}\frac{\partial g_1}{\partial\theta_2} - \frac{\partial g_2}{\partial\theta_2}\frac{\partial g_1}{\partial\theta_1} \le 0 \tag{A84}$$

But note that

$$\frac{\partial g_2}{\partial\theta_1}\frac{\partial g_1}{\partial\theta_2} - \frac{\partial g_2}{\partial\theta_2}\frac{\partial g_1}{\partial\theta_1} = -\frac{2\rho\tau\omega_0^2(\theta_1(\rho+\rho_0)+\theta_2(\tau+\tau_0))^2}{\left(\omega_0\left(\theta_1^2(\rho+\rho_0)+\theta_2^2(\tau+\tau_0)\right)+(\rho+\rho_0)(\tau+\tau_0)\right)^3} < 0, \tag{A85}$$

and so we have existence and uniqueness. ■

B.1 Welfare Analysis

In this section, we will characterize how transparency affects welfare in our benchmark model. A key challenge in defining welfare is that investors exhibit differences of opinions in our model. One approach to calculating welfare is to compute it as the sum of the unconditional expectation of each agent's utility, that is,

$$\mathcal{W} = \mathbb{E}\left[U_{S,2}\right] + \mathbb{E}\left[U_{L,1}\right], \tag{A86}$$

where we compute the unconditional expectations using the "objective distribution." At date 2, investor i's optimal demand is given by:

$$x_{i,2} = \arg\max_x \mathbb{E}_i\left[x(\phi - P_2)|F\right] - \tfrac{\lambda}{2}x^2 \tag{A87}$$

$$= \tfrac{1}{\lambda}\left(\mathbb{E}_i[\phi|F] - P_2\right) \tag{A88}$$

$$\Rightarrow U_{i,2} = \mathbb{E}_{i,2}\left[x(\phi - P_2)|F\right] - \tfrac{\lambda}{2}x^2 = \tfrac{1}{2\lambda}\left(\mathbb{E}_i[\phi|F] - P_2\right)^2. \tag{A89}$$

Equilibrium implies that $P_2 = AF$, which implies that the expected utility for agent $i \in \{L, S\}$ is:

$$U_{i,2} = \tfrac{1}{2\lambda}\left(\tfrac{1-\alpha}{2}\right)^2 F^2 \tag{A90}$$

This would be unaffected by disclosure / transparency considerations at date 2, since the unconditional distribution of α and F are unaffected by these parameters.

At date 1, L investors have optimal demand

$$x_{l,1} = \arg\max_x \mathbb{E}\left[\tfrac{1}{2\lambda}\left(\mathbb{E}_i[\phi|F] - P_2\right)^2 + x(P_2 - P_1) - \tfrac{\lambda}{2}x^2 | f_l, a_l\right] \tag{A91}$$

$$= \tfrac{1}{\lambda}\left(\mathbb{E}_l[A|a_l]\mathbb{E}_l[F|f_l] - P_1\right) \tag{A92}$$

$$U_{l,1} = \mathbb{E}\left[\tfrac{1}{2\lambda}\left(\tfrac{1-\alpha}{2}\right)^2 F^2 \middle| f_l, a_l\right] + \tfrac{1}{2\lambda}\left(\mathbb{E}_l[A|a_l]\mathbb{E}_l[F|f_l] - P_1\right)^2. \tag{A93}$$

The unconditional expected utility in this case is

$$\mathbb{E}\left[U_{l,1}\right] = \tfrac{1}{2\lambda}\mathbb{E}\left[\left(\tfrac{1-\alpha}{2}\right)^2 F^2\right] + \tfrac{1}{2\lambda}\mathbb{E}\left[\left(\mathbb{E}_l[A|a_l]\mathbb{E}_l[F|f_l] - P_1\right)^2\right] \tag{A94}$$

As a result, welfare can be expressed as

$$\mathcal{W} = \mathbb{E}\left[U_{S,2}\right] + \mathbb{E}\left[U_{L,1}\right] = \tfrac{1}{\lambda}\mathbb{E}\left[\left(\tfrac{1-\alpha}{2}\right)^2 F^2\right] + \tfrac{1}{2\lambda}\mathbb{E}\left[\left(\mathbb{E}_l[A|a_l]\mathbb{E}_l[F|f_l] - P_1\right)^2\right]. \tag{A95}$$

Proposition 7. Suppose the cost of acquisition $C(\rho_l, \tau_l, h)$ is such that an increase in transparency h leads to (strictly) more learning about fundamentals, that is, $\{\rho_l(h), \tau_l(h)\}$ are increasing in h. Then, there exists a threshold level of transparency $\bar{h}$, such that for $h > \bar{h}$, welfare is decreasing in transparency, that is, $\frac{\partial \mathcal{W}}{\partial h} < 0$.

Proof. Welfare $\mathcal{W}$ is given by

$$\mathcal{W} = \tfrac{1}{\lambda}\mathbb{E}\left[\left(\tfrac{1-\alpha}{2}\right)^2 F^2\right] + \mathcal{W}_l, \tag{A96}$$

where the first term is unaffected by transparency. To calculate the expectation in the second term, $\mathcal{W}_l$, note that

$$\mathbb{E}_l[A|a_l] = e^{\frac{\rho_l}{\rho_0+\rho_l}a_l + \frac{1}{2(\rho_0+\rho_l)} - \frac{1}{2\rho_0}} \tag{A97}$$

$$\mathbb{E}_l[F|f_l] = e^{\frac{\tau_l}{\tau_0+\tau_l}f_l + \frac{1}{2(\tau_0+\tau_l)} - \frac{1}{2\tau_0}} \tag{A98}$$

$$\Rightarrow P_1 = \int_l e^{\frac{\rho_l}{\rho_0+\rho_l}a_l + \frac{1}{2(\rho_0+\rho_l)} - \frac{1}{2\rho_0}} e^{\frac{\tau_l}{\tau_0+\tau_l}f_l + \frac{1}{2(\tau_0+\tau_l)} - \frac{1}{2\tau_0}} dl \tag{A99}$$

$$= e^{\frac{1}{2}\left(\frac{\rho_l}{\rho_0\rho_l+\rho_0^2} + \frac{\tau_l}{\tau_0\tau_l+\tau_0^2}\right)} \mathbb{E}\left[e^{\frac{\rho_l}{\rho_0+\rho_l}a_l + \frac{\tau_l}{\tau_0+\tau_l}f_l} \middle| a, f\right] \tag{A100}$$

so that

$$\mathcal{W}_l = \frac{1}{2\lambda}\mathbb{E}\left[(\mathbb{E}_l[A|a_l]\mathbb{E}_l[F|f_l]-P_1)^2\right]$$

$$= \frac{1}{2\lambda} e^{\left(\frac{\rho_l}{\rho_0\rho_l+\rho_0^2}+\frac{\tau_l}{\tau_0\tau_l+\tau_0^2}\right)} \mathbb{E}\left[\left(e^{\frac{\rho_l}{\rho_0+\rho_l}a_l+\frac{\tau_l}{\tau_0+\tau_l}f_l}-\mathbb{E}\left[e^{\frac{\rho_l}{\rho_0+\rho_l}a_l+\frac{\tau_l}{\tau_0+\tau_l}f_l}\middle|a,f\right]\right)^2\right] \quad \text{(A101)}$$

$$= \frac{1}{2\lambda} e^{\left(\frac{\rho_l}{\rho_0\rho_l+\rho_0^2}+\frac{\tau_l}{\tau_0\tau_l+\tau_0^2}\right)} \mathbb{E}\left[\text{var}\left(e^{\frac{\rho_l}{\rho_0+\rho_l}a_l+\frac{\tau_l}{\tau_0+\tau_l}f_l}\middle|a,f\right)\right]. \quad \text{(A102)}$$

Recall that for a lognormal random variable, $\mathbb{E}\left[e^x\right]=e^{\mu_x+\sigma_x^2/2}$ and $\text{var}\left[e^x\right]=e^{2\mu_x+\sigma^2}\left(e^{\sigma^2}-1\right)$, so that

$$\text{var}\left(e^{\frac{\rho_l}{\rho_0+\rho_l}a_l+\frac{\tau_l}{\tau_0+\tau_l}f_l}\middle|a,f\right)=e^{2\left(\frac{\rho_l}{\rho_0+\rho_l}a+\frac{\tau_l}{\tau_0+\tau_l}f\right)+\frac{\rho_l}{(\rho_l+\rho_0)^2}+\frac{\tau_l}{(\tau_l+\tau_0)^2}}\left(e^{\frac{\rho_l}{(\rho_l+\rho_0)^2}+\frac{\tau_l}{(\tau_l+\tau_0)^2}}-1\right),$$

which implies

$$\mathcal{W}_l = \frac{1}{2\lambda} e^{\frac{\rho_l(3\rho_l+2\rho_0)}{\rho_0(\rho_l+\rho_0)^2}+\frac{\tau_l(3\tau_l+2\tau_0)}{\tau_0(\tau_l+\tau_0)^2}}\left(e^{\frac{\rho_l}{(\rho_l+\rho_0)^2}+\frac{\tau_l}{(\tau_l+\tau_0)^2}}-1\right) \quad \text{(A103)}$$

Next, note that

$$\frac{\partial\mathcal{W}_l}{\partial\rho_l}=\frac{e^{\frac{\tau_l(3\tau_l+2\tau_0)}{\tau_0(\tau_l+\tau_0)^2}+\frac{\rho_l(3\rho_l+2\rho_0)}{\rho_0(\rho_l+\rho_0)^2}}\left(3(\rho_l+\rho_0)e^{\frac{\tau_l}{(\tau_l+\tau_0)^2}+\frac{\rho_l}{(\rho_l+\rho_0)^2}}-2(2\rho_l+\rho_0)\right)}{2\lambda(\rho_l+\rho_0)^3}, \quad \text{(A104)}$$

which is negative if and only if

$$e^{\frac{\tau_l}{(\tau_l+\tau_0)^2}+\frac{\rho_l}{(\rho_l+\rho_0)^2}} < \frac{2(2\rho_l+\rho_0)}{3(\rho_l+\rho_0)}. \quad \text{(A105)}$$

Note that $e^{\frac{\tau_l}{(\tau_l+\tau_0)^2}+\frac{\rho_l}{(\rho_l+\rho_0)^2}}$ is decreasing in ρ_l for $\rho_l>\rho_0$, but $\frac{2(2\rho_l+\rho_0)}{3(\rho_l+\rho_0)}$ is increasing in ρ_l. So, as long as

$$e^{\frac{\tau_l}{(\tau_l+\tau_0)^2}} < \frac{4}{3} \quad \text{(A106)}$$

there exists $\bar{\rho}$ such that for $\rho_l>\bar{\rho}$, $\mathcal{W}$ is decreasing in ρ_l. Moreover, the above holds for τ_l sufficiently high since the LHS is decreasing in τ_l for $\tau_l>\tau_0$. Given complementarity in information acquisition, when transparency increases sufficiently, this leads to an increase in ρ_l and τ_l to ensure that $\mathcal{W}$ is decreasing in ρ_l (and by symmetry τ_l). Since increasing transparency leads to an increase in ρ_l and τ_l, we have the result. ■

B.2 Linear specification for disagreement

The nonlinear specification of beliefs is important in generating complementarity in learning for our model. To highlight this, we consider a linear specification in this section to show how complementarity does not arise.

Suppose $\mathbb{E}_S[\phi] = F + \alpha$. Then, $P_2 = F + A$, where $A = \frac{\alpha}{2}$ and for $i \in \{L, S\}$

$$U_{i,2} = \frac{1}{2\lambda}(\mathbb{E}_i[\phi|F] - P_2)^2 = \frac{1}{2\lambda}(\mathbb{E}_i[\phi|F] - P_2)^2 = \frac{1}{2\lambda}A^2. \tag{A107}$$

Then, for long-term investors, we have

$$x_{l,2} = \arg\max_x \mathbb{E}\left[\frac{1}{2\lambda}A^2 + x(P_2 - P_1) - \frac{\lambda}{2}x^2 \middle| f_l, a_l\right] \tag{A108}$$

$$= \frac{1}{2\lambda}\left(\mathbb{E}\left[F + A \middle| f_l, a_l\right] - P_1\right) \tag{A109}$$

Analogous to the specification in the paper, suppose

$$F|f_l \sim N\left(\frac{\rho_l}{\rho_0+\rho_l} f_l, \frac{1}{\rho_0+\rho_l}\right), \text{ and } A|a_l \sim N\left(\frac{\tau_l}{\tau_0+\tau_l} a_l, \frac{1}{\tau_0+\tau_l}\right), \tag{A110}$$

so that

$$x_{l,2} = \frac{1}{2\lambda}\left(\frac{\rho_l}{\rho_0+\rho_l} f_l + \frac{\tau_l}{\tau_0+\tau_l} a_l - P_1\right) \tag{A111}$$

$$\Rightarrow P_1 = \frac{\rho_l}{\rho_0+\rho_l} F + \frac{\tau_l}{\tau_0+\tau_l} A. \tag{A112}$$

This implies

$$U_{l,0} = \frac{1}{2\lambda}\mathbb{E}\left[A^2\right] + \frac{1}{2\lambda}\mathbb{E}\left[\left(\frac{\rho_l}{\rho_0+\rho_l} f_l + \frac{\tau_l}{\tau_0+\tau_l} a_l - P_1\right)^2\right] \tag{A113}$$

$$= \frac{1}{2\lambda}\mathbb{E}\left[A^2\right] + \frac{1}{2\lambda}\mathbb{E}\left[\left(\left(\frac{\rho_l}{\rho_0+\rho_l} f_l\right)^2 + \left(\frac{\tau_l}{\tau_0+\tau_l} a_l\right)^2 + P_1^2 - 2\left(\frac{\rho_l}{\rho_0+\rho_l} f_l + \frac{\tau_l}{\tau_0+\tau_l} a_l\right) P_1\right)\right]. \tag{A114}$$

Since $f_l \sim N\left(0, \frac{1}{\rho_0} + \frac{1}{\rho_l}\right)$ and $a_l \sim N\left(0, \frac{1}{\tau_0} + \frac{1}{\tau_l}\right)$ and since agent l believes P_1 is uncorrelated with f_l and a_l (because of differences of opinions), we have

$$U_{l,0} = \frac{1}{2\lambda}\mathbb{E}\left[A^2 + P_1^2\right] + \left(\frac{\rho_l}{\rho_0+\rho_l}\right)^2\left(\frac{1}{\rho_0} + \frac{1}{\rho_l}\right) + \left(\frac{\tau_l}{\tau_0+\tau_l}\right)^2\left(\frac{1}{\tau_0} + \frac{1}{\tau_l}\right) \tag{A115}$$

$$= \frac{1}{2\lambda}\mathbb{E}\left[A^2 + P_1^2\right] + \frac{\rho_l}{\rho_0(\rho+\rho_0)} + \frac{\tau_l}{\tau_0(\tau_0+\tau_l)}, \tag{A116}$$

which implies $U_{l,0}$ is increasing in ρ_l and τ_l. However, there is no complementarity, that is, $\frac{\partial^2}{\partial\tau\partial\rho} U_{l,0} = 0$. Moreover, since

$$P_1 = \frac{\rho_l}{\rho_0+\rho_l} F + \frac{\tau_l}{\tau_0+\tau_l} A, \tag{A117}$$

it is immediate to see price efficiency is increasing in ρ_l and decreasing in τ_l. As such, an increase in fundamental transparency will always lead to an increase in price efficiency in this setting (because of lack of complementarity in learning).

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