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Decision Making and Learning in a Globalizing World*

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Abstract

We study two aspects of globalization. It allows a decision-maker to go beyond his own local experience and to learn from other decision-makers in addressing common problems. This improves the identification and diffusion of best practices. It also provides extra information to 'markets' that evaluate decision-makers: comparisons become possible. We identify conditions under which the globalization of markets helps or hurts (i) the communication among decision-makers about their own experience and (ii) the quality of the decision that is taken next. An important mediating factor is whether decision-making is centralized or decentralized.

Keywords: centralization, decentralization, learning, cheap talk, reputational concerns, globalization, policy diffusion

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1 Introduction

Many things can be done in different ways. Managers can motivate employees in different ways. Dentists can resolve tooth root infections in different ways. Teachers can teach children arithmetic in different ways. The list is virtually endless. In many areas, it is a blessing that alternative solutions to a problem exist. It enables one to effectively match a solution with the exact problem. In other areas, matching is less of an issue. In those cases a best solution, or best practice, may exist. The challenge then is to recognize the best practice and to ensure its diffusion.

The identification and diffusion of best practices raise two main problems. First, information about different practices is often dispersed. The reason is that users (teachers, doctors, politicians) usually have experience with a limited number of practices. The implication is that the search for the best practice requires communication. Second, users may identify themselves with a particular practice. Identification is likely in situations where a user is held responsible for the selection of the proper practice. A user may then be reluctant to switch to another practice out of fear of being perceived as somebody who initially selected the wrong one. Such reputational concerns may obstruct diffusion of best practices. In the present paper we address the question how features of the learning process determine the quality of communication about the performance of locally adopted practices and the diffusion of best practices. We compare a decentralized and a centralized process. In a decentralized process, users communicate with each other about their experiences (horizontal communication). Next, each user makes his own decision regarding the practice to use. In a centralized decision process, users of practices communicate with a central authority (vertical communication), and the central authority chooses the practice the users have to adopt next.

The following two examples illustrate that the above mentioned problems as to the identification and diffusion of best practices are real-world problems. First, the delivery of medical interventions varies widely from place to place.[1] This variation has been a source of worries as, most likely, some patients do not receive optimal treatment.[2] It also offers scope

[1] That variation is large is a well-established fact, see Phelps (2000).

[2] See, e.g., Eddy (1990).

for learning. In response, physicians' associations and health care authorities have exerted much effort to design learning processes in which locally gained experiences are compared, and best practices – interventions, surgical procedures, drug use – diffused. In the medical sector, expert panels are frequently used to evaluate the evidence on the effectiveness of rival practices in a given field. Given the close ties between experts and industry, and the long gestation period that characterizes the development of practices, experts tend to have vested interests and to identify with certain practices. The result, according to students of expert panels, is "process loss" due to status concerns and social pressure, meaning poor information exchange and aggregation in the meetings, and a low adoption rate of best practices afterwards.[3] Organizing these panels is therefore fraught with problems. An important organizational dimension is the degree of centralization of the process and, relatedly, the degree of freedom individual physicians have in following the outcomes of panel meetings.[4]

The European Union is another case in point. It has been promoting the so-called open method of coordination (OMC) to foster learning and the diffusion of best practices in many policy areas. The hope is that goals like EU competitiveness can be furthered by avoiding the grand questions about the best model for Europe and by taking instead a more pragmatic micro-orientation in which countries that face similar problems seek to learn from each other. Rather than relying on legislation by Brussels, the OMC leaves more freedom to member states to implement the lessons learned. Moreover, instead of applying formal sanctions to transgressors, the OMC turns to naming and shaming to expose a country's weak performance in public, and applies peer pressure if a country opposes adoption of superior policies.[5] In practice, the method is not considered to be very successful in guaranteeing a high quality learning process. It is generally felt that countries exaggerate the success of their current practices. The implementation of new ideas is very limited. Claudio Radaelli (2003, p. 12), a political scientist, argues that these disappointing results stem from a misguided view of policy makers among the proponents of the OMC. Rather than caring about the truth, they care about political capital and prestige.

Both the example of the medical sector and the example of the European Union make

[3]See Fink et al. (1984) and Rowe et al. (1991).

[4]Eddy (1990) distinguishes, in increasing degree of freedom, standards, guidelines, and options.

[5]See Pochet (2005) and Radaelli (2003).

clear that the identification and diffusion of best practices require communication, and that learning may be hampered by reputational or career concerns. By definition, learning from others requires the ability to go beyond one's local experience. It is therefore related to globalization. In the context of the search for best practices, globalization may have two effects. First, decision makers observe what other decision makers do. Globalization therefore widens the scope for learning as more experiences can be exchanged. Second, the "market" receives more information about local decision-makers. By the market we mean the people in the eyes of whom a decision-maker wants to come across as competent. For example, the peers of a medical specialist may observe that his practice gains more adherents in other areas. Or, in line with the EU example, a citizen of a country may observe that politicians or administrative bureaucracies adopt policies from another country. Therefore, as a result of globalisation, the market can compare treatments or policies across places. We will argue that this aspect of globalization has important implications for how reputational concerns affect communication and final decisions.

The main objective of our analysis is to better understand the effects of (i) the structure of the learning process (decentralization versus centralization) and (ii) the degree of globalization of the market on the quality of information exchange and, in turn, on the quality of decisions. We use an incomplete contracts approach to understand the way in which communication about the quality of locally adopted technologies is affected by the assignment of decision rights. In that sense, we follow Alonso et al. (2008) and Rantakari (2008). In particular, we do not endow some mechanism designer with the ability to first design complete contracts that prompt agents to reveal their information and next to commit to them. Clearly, a mechanism design approach would demonstrate the superiority of centralization, and would not contribute to our understanding of the effects of globalization on the decision whether or not to centralize.[6]

We present a simple two-period model of learning in which agents care both about adopt-

[6] See Mookherjee (2006) for an excellent survey on the centralization-decentralization debate from a mechanism design perspective. It is perhaps worth noting that in the context of a search for best practices a central authority does not always exist. A temporary one (e.g., a health care consensus panel) must be created. It might be hard for such a temporary central authority to commit to mechanisms.

ing the better practice and about acquiring a reputation for finding the better practice (medical intervention, policy etc.). Through learning-by-doing each agent gains information about the value of his own practice. We assume this information to be private and non-verifiable. The information exchanged then amounts to cheap talk. In the conclusion, we briefly discuss how our main results would be affected if information were verifiable.

We now turn to a discussion of our results. In period one, an agent adopts a practice he considers to be the better one. In case of a *decentralized learning process*, the period two decision is characterized by inertia. This arises as, in equilibrium, continuation of one's initial technology commands a higher reputation than change as it signals higher observed values of the practice and therefore a better initial choice. Hence, given the information an agent has, he sticks to his initial choice even though it would have been first-best to switch. The information he has is partly gained through learning-by-doing, partly by what others are willing to share with him. The quality of information exchange in the decision-making process is high if markets are unaware of practices used by other agents ('local markets'). An agent can only gain by listening to others, and has nothing to loose by truthfully revealing his own experience, as his reputation does not depend on the practice that the other agent adopts in period two.

When markets gain a better understanding of the technologies that are initially adopted in other places thanks to progressing globalization ('global markets') an agent's reputation starts to depend on what technologies he and others use. His reputation is particularly strong if others start to adopt "his" initial technology. As a result, the role of communication in the decision-making process becomes strategic. Global markets create competition. An agent wants to convince others that "his" technology is best. We show that communication breaks down completely: an agent only learns which technology has been used in other places. This is reminiscent of the experience of the OMC, a case of decentralized learning with global markets. We present conditions under which the globalization of markets in case learning is decentralized hurts welfare.

Decision-making in a *centralized learning process* does not suffer from inertia as the center only cares about the technology's value. But the center depends on the agents to provide him with information. An agent now faces a trade-off. On the one hand, as the agent has no decision-making power, he wants to make sure that the center is well-informed. On the other hand, his reputational concerns imply that he wants the center to impose "his" technology at either site. In equilibrium, each agent sends coarse information about his own practice. We derive conditions under which the globalization of markets in case learning is centralized improves welfare. We also derive the conditions under which, in the case of local markets, the quality of information exchange is so poor under centralized learning (vis-à-vis decentralized learning) that it offsets the improved decision-making *conditional* on information. Furthermore, we establish that in the case of global markets a centralized learning process uniformly outperforms a decentralized learning process. One reason is that with global markets communication between the agents and the center does not vanish, however much the agents care about their reputations.

The paper is organized as follows. The next section discusses the related literature. In Section 3, we present the model. Section 4 analyses isolated agents, a benchmark situation in which agents can learn from their own past experience only. In section 5 we analyse decentralized learning, with local and global markets. In section 6 we perform the same analysis for centralized learning. Section 7 contains the comparisons. Section 8 concludes.

2 Related Literature

Our paper contributes to the literature that studies how the quality of information exchange is determined by the features of the decision-making process. This literature takes an incomplete contracts approach to decision-making in which commitment is limited to the ex ante assignment of decision rights. As a result, communication among agents amounts to cheap talk. In their seminal paper, Crawford and Sobel (1982) show that the quality of cheap talk depends on the degree of alignment between the interests of the informed sender and the uninformed decision-maker (receiver). In Crawford and Sobel, and in the literature on cheap talk in general, this degree of alignment is exogenously given. In our model, by contrast, this degree is determined in equilibrium. The reason is that senders are concerned with their reputations. These reputations are determined in equilibrium. There is now a growing literature that explores how characteristics of decision-making processes influence the quality of communication, both in political science[7], and in economics[8]. The current paper differs from the existing literature in its focus on the possibilities for learning-by-doing and learning from the experience of others in a context where agents have reputational concerns.

The desirability of decentralization or centralization is also studied by Alonso et al. (2008) and by Rantakari (2008) in the context of a multidivisional firm. Each division benefits from adapting its decision to its own market circumstances and from coordinating its decision with those of the other divisions. Divisions are privately informed about their market circumstances. They can either exchange information and next decide independently of each other what decisions to take or they can report information to headquarters which then decides for both divisions. They show that even if coordination becomes of overriding concern to the firm, decentralization may still outperform centralization due to the difference in quality of communication.[9]

As Alonso et al. and Rantakari we study the effect of the assignment of decision rights on the quality of communication and of the final decisions taken. The situation we analyse, however, is quite different. In our paper, there are no local circumstances to which a decision should ideally be adapted, nor is there a need to coordinate per se. Instead, there is room for learning from each other's past experience (to identify the better technology), resistance to change (because of reputational concerns), and possibly the desire to convince the other to adopt one's technology (due to reputational concerns in case of global markets).

There is a growing literature on reputational concerns. Holmstrom (1999) studies the incentives such concerns give to exert productive effort if there is uncertainty about an agent's ability level. If there is uncertainty about an agent's ability to 'read' or predict the state of the world one speaks of 'expert' models. Experts use the recommendations that they give, the implementation decision that they take, or the effort they exert to convince the market of their expertise.[10] Part of this expert literature looks at the effects of information

[7] See e.g., Gilligan and Krehbiel (1987), Austen-Smith (1990), Coughlan (2000), and Austen-Smith and Feddersen (2005).

[8] See e.g. Dessein (2002, 2007), Visser and Swank (2007), Alonso et al. (2008), Rantakari (2008), and Friebel and Raith (2010).

[9] Friebel and Raith (2010) study how the scope of the firm affects the quality of strategic information transmission between a division and head quarters.

[10] Scharfstein and Stein (1990) and Ottaviani and Sorensen (2001, 2006) deal with the advice given by

disclosure ('transparency') about an expert's actions and about the outcomes of decisions.[11] Clearly, the present paper is related to that literature. Globalization of markets, for example, amounts to increased disclosure of information that is useful in evaluating an agent's ability. We show that it destroys communication in case of decentralized learning, but improves it in case of centralized learning. That is, the same form of transparency may give rise to very different effects depending on the institutions in which it is introduced.

Our paper is also related to the literature on laboratory federalism and policy diffusion in political science, see Oates (1999). In an interesting recent paper, Volden, Ting, and Carpenter (2008) study what happens if policy makers trade off policy effectiveness at solving problems and political preferences. They compare the adoption patterns of states that act independently and learn from their own past performance at addressing common problems with the patterns that arise if states learn from each other. Our focus is different from theirs as we study the quality of information exchange among decision-makers, compare centralized and decentralized decision-making, and study the effect of information that markets have on adoption decisions.

Finally, our paper is related to the existing literature on learning from others. This literature is, however, methodologically quite different from ours. In the existing literature, it is *assumed* that either an agent observes the true value of the actions taken by others, whether the environment is strategic[12] or not[13], or that no such information is observed at

experts. Milbourn et al (2001) and Suurmond et al. (2004), deal with the projects an expert implements and the effort he exerts to become informed.

[11] See Suurmond et al. (2004) and Prat (2005) in a single-agent setting, and Levy (2007) and Swank and Visser (2009) in a committee setting.

[12] See the discussion of social learning in a strategic experimentation game in Bergemann and Välimäki (2006). In this literature, it is assumed that an agent perfectly observes both the technology others use and the true value they obtain. It is not clear that an agent, if he could, would not want to deviate from a strategy of truthfully revealing the value of the technology he has gained experience with. It seems that he would benefit from exaggerating the value as this would make adoption by others more likely. As a result, more (public) information would become available about this technology, and the deviator would benefit from an improved estimate of the technology's value.

[13] See Bala and Goyal (1998) for a model of learning in non-strategic networks, and Ellison and Fudenberg (1993, 1995) and Banerjee and Fudenberg (2004) for analyses of word-of-mouth communication in non-strategic environments.

all[14]. Furthermore, inertia is an *exogenous* factor. For example, in the literature on word-of-mouth communication, it is assumed that only a given fraction of agents updates its decisions once new information becomes available. In our paper both the quality of the information exchange and the degree of inertia are equilibrium outcomes. Were it not for the reputational concerns, the problem the agents are facing in our model, that of choosing one technology out of many, is similar to a common value bandit problem in which the bandit's arms represent the technologies of unknown, but common, value.[15] The main difference is that in a bandit problem the distribution of the value of a technology does not change with an observation of the value of *another* technology, whereas in our problem it does. This stems from the fact that in our model the initial signal an agent receives provides information about the better technology. The higher is the observed value of a technology Y, the higher is the probability that the agent identified the better technology. And this means that it becomes more likely that the value of the other technology is lower than the actual value of Y.

The fact that in our model the quality of information exchange and the degree of inertia are endogenous, and that a key assumption of the statistical bandit model is violated imply that a general analysis of the asymptotic behaviour of the decision-making processes described here is difficult and beyond the scope of this paper. Instead, we compare the behaviour of agents across various decision-making processes in a two-period setting.

3 A model of learning-by-doing and learning from others with reputational concerns.

There are two sites (hospitals, states, etc.), $i \in \{1, 2\}$, and one problem. There is an agent i at each site. Often, j will denote "the other site" or "the other agent," $j \neq i$. The problem has to be addressed at each site both in period $t = 1$ and in $t = 2$. There are two possible technologies (policies, interventions, etc.) $X \in \{Y, Z\}$, one of which has to be used to

[14] In the literature on informational herding, communication between decision-makers is excluded although the environment in non-strategic. See e.g. Bikhchandani, Hirshleifer and Welch (1998). See Çelen, Kariv and Schotter (2008) for a first experimental analysis of social learning from actions and advice.

[15] See Bergemann and Välimäki (2006) for a concise survey of bandit problems.

address the problem at each site in each period. The technology adopted at site i in period t is denoted by $X_{i,t}$. A priori, the value of technology X is unknown, but independent of time and site. Moreover, we assume that it is a random draw from a continuous and strictly increasing distribution function $F_X(\cdot)$ and associated density function $f_X(\cdot)$, with support $[0,1]$. Note that we use X both to denote a technology and its random value. We assume that the values Y and Z are iid, $F_Y = F_Z = F$. We use lower case letters, like x, to denote a possible value of technology X, such that $x \in [0,1]$. As strategies will be defined in terms of X (or x), it will be useful to let X^C (or x^C) refer to "the other technology". That is, if $X = Y$, then $X^C = Z$, etc.

The agents' diagnostic ability levels $\theta_i \in \left\{\underline{\theta}, \bar{\theta}\right\}$ and the state of the world $(y,z) \in [0,1]^2$ are exogenously given. The ability levels and the state of the world are all statistically independent, with $\pi = \Pr\left(\theta_i = \bar{\theta}\right) \in (0,1)$ for $i \in \{1,2\}$.

At the beginning of period $t = 1$, agent i at site i receives a private, non-verifiable, signal $s_i \in \left\{s^Y, s^Z\right\}$ about which technology solves the problem best. The informativeness of the signal depends on the agent's ability: $\Pr\left(s^X | x > x^C, \bar{\theta}\right) = 1$, $\Pr\left(s^X | x^C > x, \bar{\theta}\right) = 0$, $\Pr\left(s^X | x > x^C, \underline{\theta}\right) = \Pr\left(s^X | x^C > x, \underline{\theta}\right) = 1/2$, for $X \in \{Y, Z\}$. That is, if i is highly able, $\theta_i = \bar{\theta}$, the signal (diagnosis) reveals with probability one the better technology: $\Pr\left(x > x^C | s^X, \bar{\theta}\right) = 1$ for $X \in \{Y, Z\}$. Hence, conditional on s^X and $\theta = \bar{\theta}$, X is distributed as the maximum of two iid random variables, $F_X\left(x | s^X, \bar{\theta}\right) = F(x)^2$. On the other hand, if i is less able, $\theta_i = \underline{\theta}$, the signal is uninformative about the relative quality of the technology: $F_X\left(x | s^X, \underline{\theta}\right) = F(x)$. Note that an agent does not get a signal about his ability. Instead, π is the common prior.[16] Still in period 1, i next decides which technology X to adopt on the basis of his signal s_i. At the end of the period he learns the value x of the chosen technology (learning-by-doing).

At this point, it is worth emphasizing that the focus of our analysis will be on period 2. As mentioned in the introduction, we intend to understand the pros and cons of alternative learning processes in situations where (i) agents have gained experiences with different technologies, treatments, or policies and (ii) there is scope for learning. In our model, period

[16] What matters for the results is that if $\theta_i = \bar{\theta}$, member i has a higher likelihood of correctly assessing the state of the economy than if $\theta_i = \underline{\theta}$.

1 can be interpreted as the history in which agents gained information. We model history to stress that past decisions matter for current decisions, for example, through reputational concerns.

We distinguish three learning processes p that characterize period $t = 2$. Such a process consists of a decision-making stage, possibly preceded by a communication stage. In case there is a communication stage, agent i sends a message about the quality of the technology adopted at site i in period $t = 1$. The receiver of this message depends on the process p. We assume that agent i, if and when he sends a message, knows the technology (*not* its value) that j has used in $t = 1$ when he sends a message. This is often the relevant case, as agents may well be aware that other technologies are used, without knowing their quality. Hence, a communication strategy $\mu_i^{\mathsf{p}}(\cdot)$ is a conditional probability distribution. Let $\mu_i^{\mathsf{p}}(m_i|s_i, x_{i,1}, X_{j,1})$ be the likelihood that i sends message $m_i \in M$, where $M = [0,1]$ is a message space, in case his signal equals s_i, the observed value of $X_{i,1}$ equals $x_{i,1}$, and agent j uses technology $X_{j,1}$. Next, a decision maker determines which technology $X_{i,2}$ is adopted at site i at time $t = 2$. Who this decision maker is depends on the decision process p. Let $I_i^{\mathsf{p}} \in \mathcal{I}_i^{\mathsf{p}}$ be the information this person has at the beginning of the decision-making stage. It depends on the process p. The decision strategy d_i^{p} determines the relationship between I_i^{p} and the technology adopted at site i.

(i) In case of isolated agents (p=ia), agents do not communicate, and therefore do not know what technology is being used at the other site. Hence, $\mathcal{I}_i^{\mathsf{ia}} = \{s^Y, s^Z\} \times [0,1]$: the information i has is a signal and the value of the technology used in $t = 1$. Agent i decides on $X_{i,2}$. Let $d_i^{\mathsf{ia}}(s_i, x_{i,1}) \in \{Y, Z\}$ denote the technology that i uses in $t = 2$ given his signal s_i and the observed value $x_{i,1}$.

(ii) In case of decentralized learning (p=dl), each agent i simultaneously sends a message m_i to the other agent concerning the value of the technology he has adopted in $t = 1$. So, $\mathcal{I}_i^{\mathsf{dl}} = \{s^Y, s^Z\} \times [0,1] \times M \times \{Y, Z\} \times M$. That is, in addition to the information in case of p=ia, and the message he sends to j, i also knows the technology $X_{j,1} \in \{Y, Z\}$ adopted at the other site, and the message $m_j \in M$ about the value of that technology. Agent i next decides on $X_{i,2}$. Let $d_i^{\mathsf{dl}}(s_i, x_{i,1}, m_i, X_{j,1}, m_j) \in \{Y, Z\}$ denote the technology that i adopts in $t = 2$ given I_i^{dl}.

(iii) In case of centralized learning (p=cl), each agent i simultaneously sends a message m_i concerning the value of the technology he has adopted in $t = 1$ to "the center." Hence, $\mathcal{I}_C^{\mathsf{cl}} = \{Y, Z\}^2 \times M^2$ represents the center's information set: information about which technology has been adopted at each site, and a message concerning the value of each technology. Next, the center decides which technology is adopted at either site. Let $d_C^{\mathsf{cl}}(X_{1,1}, X_{2,1}, m_1, m_2) \in \{Y, Z\} \times \{Y, Z\}$ denote the correspondence indicating for given technologies used at either site and for given messages sent by the agents the technology that is used at sites 1 and 2, respectively in $t = 2$. As no confusion can arise, we write $\mathcal{I}_C$ instead of $\mathcal{I}_C^{\mathsf{cl}}$, and d_C instead of d_C^{cl}.

As noted in the introduction, globalization has two effects: first, it allows a previously isolated agent to learn from the experience of others, and second, it offers more information about a local agent to "the market". The market at site i at time t is characterized by its information, $\Omega_{i,t}$. An agent learns about technologies and their values through learning-by-doing and by listening to others. We assume that the market knows less about technologies than an agent does: markets only know certain patterns of technology adoption. In particular, in $t = 1$, $\Omega_{i,1} = \{X_{i,1}\}$ for $i \in \{1, 2\}$. For $t = 2$, we distinguish two cases. Say that markets are *local*, if markets possess knowledge about site-specific adoption patterns only, $\Omega_{i,2} = \{X_{i,1}, X_{i,2}\}$ for $i \in \{1, 2\}$. Say that markets are *global*, if markets possess knowledge about all adoption patterns, $\Omega_{i,2} = \{X_{i,1}, X_{j,1}, X_{i,2}, X_{j,2}\}$ for $i \in \{1, 2\}$. We call $(X_{i,1}, X_{j,1}, X_{i,2}, X_{j,2})$ the *adoption vector*, indicating which technologies are adopted in $t = 1$ at sites i and j, and in $t = 2$ at sites i and j, respectively. Clearly then, we assume that learning-by-doing gives the agent an informational advantage over his market: whereas an agent learns the true value of the technology he uses, his market only observes certain adoption patterns.[17]

To analyse the effect of reputational concerns, we assume that an agent's utility depends on the value of the technology adopted at his site and on his market's assessment of his ability. The ex post belief that i is highly able conditional on the information set $\Omega_{i,t}$

[17] What is important for the results is that agent i has an informational advantage over his market. As long as such an advantage exists, the agent will use the technology adoption decision to influence the market's view on his ability, and the communication strategies will qualitatively remain the same.

equals $\hat{\pi}_{i,t}(\Omega_{i,t}) = \Pr\left(\theta_i = \bar{\theta}|\Omega_{i,t}\right)$. If x is the value of the technology $X_{i,t}$ that i adopts, and the market's information set equals $\Omega_{i,t}$, then the period t utility of agent i equals $U(X_{i,t}) = x + \lambda\hat{\pi}_{i,t}(\Omega_{i,t})$, with $\lambda > 0$ the relative weight of reputational concerns. We ignore time discounting. The center's utility equals the sum of the values of the technologies adopted in $t = 2$, $U_C(X_{1,2}, X_{2,2}) = x_{1,2} + x_{2,2}$.

Different decision processes cause differences in behaviour in the second period, but not in the first. This will be readily apparent from the analysis in the following sections. Independent of the decision process, period $t = 1$ behaviour that maximizes agent i's utility is to follow his signal: $X_{i,1} = Y$ if and only if $s_i = s^Y$. This maximizes the expected value of the technology and minimizes the probability of changing (or having to change) technology in period 2.

An equilibrium consists of a communication strategy $\mu_i(\cdot)$ for each agent, a belief function $f_i(\cdot|I)$ for each decision maker, a decision strategy $d_i(\cdot)$ for each decision maker, and ex post assessments $\hat{\pi}_{i,t}(\cdot)$ for each market. We use the concept of Perfect Bayesian Equilibrium (from now on, equilibrium) to characterize behaviour. This requires (i) that the communication strategies are optimal for each type given decision makers' strategies and market assessments; (ii) that the decision strategy is optimal given the belief functions and market assessments; (iii) that beliefs and market assessments are obtained using Bayes rule. Because of the inherent symmetry, we write the analysis from the point of view of agent $i = 1$ and assume that $s_1 = s^Y$. Of course, $s_2 \in \left\{s^Y, s^Z\right\}$. We ignore babbling equilibria if an equilibrium in which information is transmitted exists.

4 Isolated agents

Once agent 1 has followed his signal s^Y in period 1 and observed value y, he has to decide whether to continue with his technology. Note that having received s^Y and next observing y allows an agent to update the expected value of the other technology,

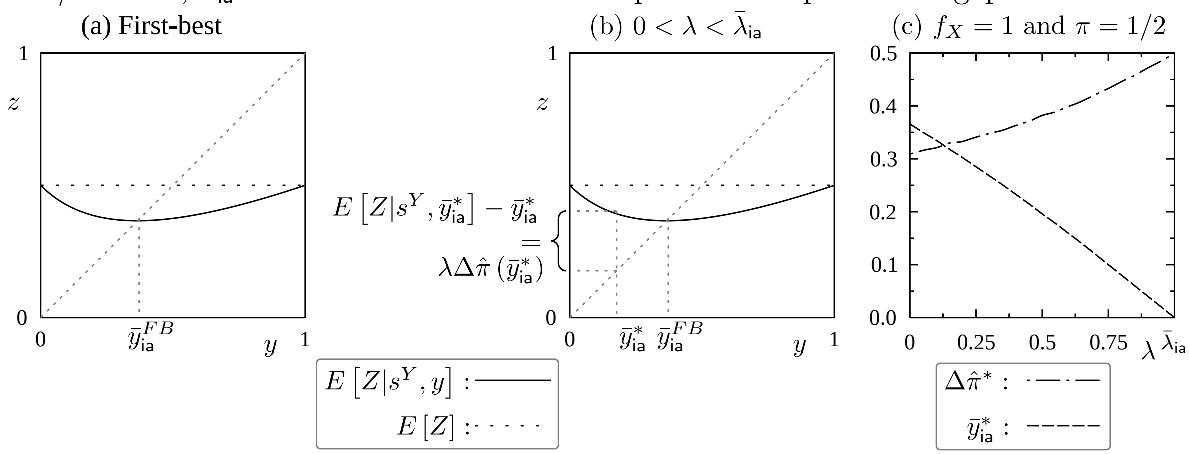
$$E\left[Z|s^Y, y\right] = \Pr\left(\bar{\theta}|s^Y, y\right) E\left[Z|s^Y, y, \bar{\theta}\right] + \Pr\left(\underline{\theta}|s^Y, y\right) E\left[Z\right], \tag{1}$$

where we have used that $E\left[Z|s^Y, y, \underline{\theta}\right] = E\left[Z\right]$. Two effects of y can be distinguished. First, the larger is y, the more likely it is that the agent is highly able and correctly identified the more valuable technology. This is the $\Pr\left(\bar{\theta}|s^Y, y\right)$ term. Second, conditional on the agent being highly able, a higher value of y increases the expected value of Z. This is the $E\left[Z|s^Y, y, \bar{\theta}\right]$ term. Of course, $E\left[Z|s^Y, y, \bar{\theta}\right] \leq E[Z]$. The following lemma summarizes some characteristics of $E\left[Z|s^Y, y\right]$.

Lemma 1 *The expected value of Z given $s_i = s^Y$ and y satisfies: (a) $E\left[Z|s^Y, 0\right] = E\left[Z|s^Y, 1\right] = E[Z]$, and $E\left[Z|s^Y, y\right] < E[Z]$ for $y \in (0,1)$; (b) $E\left[Z|s^Y, y\right]$ is decreasing in y for $y < E\left[Z|s^Y, y\right]$, increasing for $y > E\left[Z|s^Y, y\right]$, and $y = E\left[Z|s^Y, y\right]$ has a unique solution.*

This lemma is illustrated in Figure 1, panel a. The horizontal line represents the unconditional expectation $E[Z]$, and the conditional expectation $E\left[Z|s^Y, y\right]$ is a convex function of y.

Figure 1: Isolated Agents. Panel a depicts the first-best threshold value; panel b the equilibrium threshold value $\bar{y}^*_{\mathsf{ia}}$ for $\lambda < \bar{\lambda}_{\mathsf{ia}}$; panel c reports the equilibrium values for $f_X = 1$ and $\pi = 1/2$. Thus, $\bar{\lambda}_{\mathsf{ia}} = 1$. Note that $\Delta\hat{\pi}^*$ is the equilibrium reputational gap.



Ignore reputational concerns for the moment. Given $I_1^{\mathsf{ia}} = \left\{s^Y, y\right\}$, the decision strategy that maximizes the expected value of the technology adopted at site 1 in the second period, the first-best strategy, is to stick to the existing technology if and only if $y \geq E\left[Z|s^Y, y\right]$. It follows from lemma 1, part (b), and it is clear from Figure 1, panel a, that the first-best decision strategy is a *single-threshold strategy*,

$$d_1^{\mathsf{ia}}\left(I^{\mathsf{ia}}; \bar{t}\right) = \begin{cases} Y & \text{if } y \geq \bar{t} \\ Z & \text{otherwise,} \end{cases}$$

with $\bar{t} = \bar{y}_{\mathsf{ia}}^{FB}$ and where $\bar{y}_{\mathsf{ia}}^{FB}$ solves $\bar{y}_{\mathsf{ia}}^{FB} = E\left[Z|s^Y, \bar{y}_{\mathsf{ia}}^{FB}\right]$.

Besides being interested in picking the most valuable technology, an agent is also interested in his reputation. Consider a threshold decision strategy and any threshold value $\bar{t} \in (0,1)$. Recall that in case of isolated agents, markets only have local knowledge. Let $\hat{\pi}(Y, X_{1,2}; \bar{t})$ denote the reputation, obtained using Bayes' rule, if $X_{1,2} \in \{Y, Z\}$, and the agent uses the threshold $\bar{t}$. Then,[18]

$$\hat{\pi}_1(Y,Y;\bar{t}) = \frac{1+F(\bar{t})}{1+F(\bar{t})\pi}\pi > \pi > \hat{\pi}_1(Y,Z;\bar{t}) = \frac{F(\bar{t})}{F(\bar{t})\pi + (1-\pi)}\pi. \tag{2}$$

Irrespective of $\bar{t}$, continuation commands a higher reputation than switching to the other technology. Continuation suggests having observed a sufficiently high value of y. A highly able agent is more likely to have implemented a technology that generates a high value than a less able agent. Hence, as an agent cares about his reputation, he wants to deviate from the first-best decision rule by lowering the hurdle that his initial technology should pass for its continuation. The agent wants to give up technological adequacy for reputational benefits. We will call the difference $\hat{\pi}_1(Y,Y;\bar{t}) - \hat{\pi}_1(Y,Z;\bar{t})$ the *reputational gap*. It is the source of the distortion. Proposition 1 describes equilibrium behaviour of an isolated agent.

Proposition 1 *In case of isolated agents, and for $\lambda < \bar{\lambda}_{\mathsf{ia}} = E[Z]/\pi$, there exists an equilibrium in whicth the decision strategy is a single-threshold strategy with threshold value $\bar{y}_{\mathsf{ia}}^*$ that satisfies*

$$\lambda\left[\hat{\pi}_1(Y,Y;\bar{y}_{\mathsf{ia}}^*) - \hat{\pi}_1(Y,Z;\bar{y}_{\mathsf{ia}}^*)\right] = E\left[Z|s^Y, \bar{y}_{\mathsf{ia}}^*\right] - \bar{y}_{\mathsf{ia}}^*, \tag{3}$$

with $\bar{y}_{\mathsf{ia}}^* \in \left(0, \bar{y}_{\mathsf{ia}}^{FB}\right)$. $\bar{y}_{\mathsf{ia}}^*$ is a decreasing function of λ.[19] *For $\lambda \geq \bar{\lambda}_{\mathsf{ia}}$, $\bar{y}_{\mathsf{ia}}^* = 0$, i.e., agent 1 always continues his initial technology, and $\hat{\pi}_1(Y,Y;0) = \pi$ and $\hat{\pi}_1(Y,Z;0) = 0$.*

Eq (3) is illustrated in Figure 1, panel b. At the threshold value $\bar{y}_{\mathsf{ia}}^*$ the agent is indifferent between sticking to Y and switching to Z. This can also be seen by rewriting (3) as $\bar{y}_{\mathsf{ia}}^* + \lambda\hat{\pi}_1(Y,Y;\bar{y}_{\mathsf{ia}}^*) = E\left[Z|s^Y, \bar{y}_{\mathsf{ia}}^*\right] + \lambda\hat{\pi}_1(Y,Z;\bar{y}_{\mathsf{ia}}^*)$. The left-hand side equals the value

[18] Deriviations can be found in the proof of Proposition 1 in the Appendix.

[19] We cannot exclude the possibility of multiple equilibria in general. In case of multiple equilibria, we show that the highest and the lowest equilibrium values of $\bar{y}_{\mathsf{ia}}^*$ are decreasing functions of λ. We have established numerically that in case of the uniform distribution, the equilibrium is unique, in this and all other sections.

of continuing with Y if its observed value equals $\bar{y}^*_{\mathsf{ia}}$, whereas the left-hand side equals the value of switching technology for the same observed value of Y. It follows from (2) that the lower $\bar{y}^*_{\mathsf{ia}}$ is, the lower is the reputation the agent commands in case of sticking to the original technology *and* in case of switching technologies. If the hurdle for continuation is lowered, passing the hurdle becomes a less convincing signal of diagnostic ability. At the same time, not passing a lower hurdle becomes a stronger signal of incompetence. It can be checked that the reputational gap increases the lower is $\bar{y}^*_{\mathsf{ia}}$. As the reputational gap is still strictly positive for a threshold value equal to zero, it follows from (3) that for $\lambda \geq \bar{\lambda}_{\mathsf{ia}}$ $\bar{y}^*_{\mathsf{ia}} = 0$: the agent will continue with his initial choice of technology irrespective of its value. Figure 1, panel c illustrates the proposition for a uniform distribution and $\pi = 1/2$. It shows the equilibrium values of $\bar{y}^*_{\mathsf{ia}}$ and $\hat{\pi}_1 (Y, Y; \bar{y}^*_{\mathsf{ia}}) - \hat{\pi}_1 (Y, Z; \bar{y}^*_{\mathsf{ia}})$.

5 Decentralized learning process

We begin by describing first-best behaviour in a decentralized process. In the communication stage each agent truthfully reveals his private information. Say that 1 *truthfully reveals* his private information if, for all $y \in [0, 1]$, and all $X_{2,1} \in \{Y, Z\}$, $\Pr\left(m_1 | s^Y, y, X_{2,1}\right) = 1$ if $m_1 = y$ and $\Pr\left(m_1 | s^Y, y, X_{2,1}\right) = 0$ otherwise. Next, the first-best decision strategy equals

$$d_1^{\mathsf{dl}}\left(I_1^{\mathsf{dl}}; \bar{y}_{\mathsf{S}}^{FB}\right) = \begin{cases} Y & \text{if } X_{2,1} = Y \text{ and } y \geq \bar{y}_{\mathsf{S}}^{FB} \\ Y & \text{if } X_{2,1} = Z \text{ and } y \geq z \\ Z & \text{otherwise,} \end{cases}$$

where $\bar{y}_{\mathsf{S}}^{FB}$ satisfies $\bar{y}_{\mathsf{S}}^{FB} = E\left[Z | s^Y, s^Y, \bar{y}_{\mathsf{S}}^{FB}\right]$. That is, if both agents adopted the *same* technology, each agent should continue this technology if its value is larger than $\bar{y}_{\mathsf{S}}^{FB}$.[20] If instead agents adopted different technologies, they should next choose the one with superior performance. In 5.1 we study equilibrium behaviour in case of local markets, and in 5.2 we turn to global markets. In 7.1, we compare the performance of decentralized learning under local and global markets.

[20] Of course, the fact that both experts used the same technology in the first period bodes well for the superiority of this technology: $\bar{y}_{\mathsf{S}}^{FB} < \bar{y}_{\mathsf{ia}}^{FB}$.

5.1 Local markets

By definition, local markets only know the technology that is adopted locally. Can truthful revelation be part of an equilibrium? With agent 1's reputation independent of what the other agent decides, and with agent 1 being free to choose what technology to adopt in $t = 2$, truthful revelation of the technology's value is a weakly dominant communication strategy for each agent. Absent any motive to influence the other agent, the quality of the information exchange is high.

Once communication has taken place, each agent independently decides whether to continue with his original technology or to switch to the other technology. Let a *double-threshold strategy* $d_1^{\mathsf{dl}}\left(I_1^{\mathsf{dl}}; \bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}}\right)$ with thresholds $(\bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}}) \geqq 0$ be defined as

$$d_1^{\mathsf{dl}}\left(I_1^{\mathsf{dl}}; \bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}}\right) = \begin{cases} Y & \text{if } X_{2,1} = Y \text{ and } y \geq \bar{t}_{\mathsf{S}} \\ Y & \text{if } X_{2,1} = Z \text{ and } y \geq m_2 - \bar{t}_{\mathsf{D}} \\ Z & \text{otherwise.} \end{cases}$$

That is, agent 1 continues with his original technology Y (i) if both agents used the same technology and its value exceeds $\bar{t}_{\mathsf{S}}$; or (ii) if the agents used different technologies, but the other technology is either less valuable or its superior performance does not exceed by a margin larger than $\bar{t}_{\mathsf{D}}$ the value of the current technology. Let $\hat{\pi}_1(Y, X; \bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}})$ denote 1's reputation if he uses $d_1^{\mathsf{dl}}(\cdot)$, and adopts $X_{1,2} = X$ in period 2, with $X \in \{Y, Z\}$.

To see that an agent wants to distort the decision on $X_{1,2}$, suppose 1 were to use the first-best threshold values, $(\bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}}) = \left(\bar{y}_{\mathsf{dl}}^{FB}, 0\right)$. If 1 continues with his initial technology, his market would deduce that either the same technology was used at the other site and its observed value exceeded $\bar{y}_{\mathsf{dl}}^{FB}$, or that the other site used the other technology which proved to be of inferior quality. Either event strengthens 1's reputation. Analogously, discontinuing a technology hurts a reputation. As a result, reputational concerns induce an agent to distort the decision in $t = 2$. If both agents adopted Y in $t = 1$, then agent 1 sticks to this technology if and only if $y + \lambda\hat{\pi}_1(Y, Y; \bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}}) \geq E\left[Z | s^Y, s^Y, y\right] + \lambda\hat{\pi}_1(Y, Z; \bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}})$. Similarly, in case agents adopted different technologies, agent 1 wants to continue with Y iff $y + \lambda\hat{\pi}_1(Y, Y; \bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}}) \geq z + \lambda\hat{\pi}_1(Y, Z; \bar{t}_{\mathsf{S}}, \bar{t}_{\mathsf{D}})$. Proposition 2 describes equilibrium behaviour.

Proposition 2 *Define* $\underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} = E[Z]/\hat{\pi}_1(Y,Y;0,E[Z])$ *and* $\bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} = 1/\pi$. *In case of decentralized learning with local markets, an equilibrium exists in which*
(i) it is a weakly dominant communication strategy to truthfully reveal private information;
(ii) the belief functions are $\Pr(x_{2,1}|m_2) = 1$ *for* $x_{2,1} = m_2$ *and* $\Pr(x_{2,1}|m_2) = 0$ *for* $x_{2,1} \neq m_2$;
(iii) the decision strategy is a double-threshold strategy. For $\lambda < \underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}$, *threshold values* $(\bar{t}_{\mathsf{S}}^*, \bar{t}_{\mathsf{D}}^*)$ *satisfy*

$$\lambda[\hat{\pi}_1(Y,Y;\bar{t}_{\mathsf{S}}^*,\bar{t}_{\mathsf{D}}^*) - \hat{\pi}_1(Y,Z;\bar{t}_{\mathsf{S}}^*,\bar{t}_{\mathsf{D}}^*)] = E\left[Z|s^Y,s^Y,\bar{t}_{\mathsf{S}}^*\right] - \bar{t}_{\mathsf{S}}^* \tag{4}$$

$$\lambda[\hat{\pi}_1(Y,Y;\bar{t}_{\mathsf{S}}^*,\bar{t}_{\mathsf{D}}^*) - \hat{\pi}_1(Y,Z;\bar{t}_{\mathsf{S}}^*,\bar{t}_{\mathsf{D}}^*)] = \bar{t}_{\mathsf{D}}^*, \tag{5}$$

with $\bar{t}_{\mathsf{S}}^* \in \left(0, \bar{y}_{\mathsf{S}}^{FB}\right)$ *and* $\bar{t}_{\mathsf{D}}^* \in (0,1)$. *For* $\lambda \in [\underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}, \bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}})$, *threshold values are* $(0, \bar{t}_{\mathsf{D}}^*)$ *and* $\bar{t}_{\mathsf{D}}^*$ *solves* $\lambda\hat{\pi}_1(Y,Y;0,\bar{t}_{\mathsf{D}}^*) = \bar{t}_{\mathsf{D}}^*$. *Finally, for* $\lambda \geq \bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}$, *threshold values equal* $(0,1)$.

Figure 2, panels a and b show the structure of the equilibrium. For $\lambda < \underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}$, see panel a and Eqs (4) and (5), in equilibrium the size of the distortions, $E\left[Z|s^Y,s^Y,\bar{t}_{\mathsf{S}}^*\right] - \bar{t}_{\mathsf{S}}^*$ and $\bar{t}_{\mathsf{D}}^*$, and the value of the reputational gap, $\lambda[\hat{\pi}_1(Y,Y;\bar{t}_{\mathsf{S}}^*,\bar{t}_{\mathsf{D}}^*) - \hat{\pi}_1(Y,Z;\bar{t}_{\mathsf{S}}^*,\bar{t}_{\mathsf{D}}^*)]$, are the same. The loss in technological value due to the distortion should in either case be compensated by the same boost in reputation. At $\lambda = \underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}$, $\bar{t}_{\mathsf{S}}^* = 0$, and $\bar{t}_{\mathsf{D}}^* = E[Z]$. Then, the market deduces from (Y,Z) that $y < z$, and so 1 initially picked the inferior technology, $\hat{\pi}_1(Y,Z;0,E[Z]) = 0$. Also, $\hat{\pi}_1(Y,Y;0,E[Z]) > \pi$ as the market infers from (Y,Y) that either both agents initially received s^Y, or that the other agent received s^Z but $y \geq z - \bar{t}_{\mathsf{D}}^*$. Either possibility boosts agent 1's reputation. It follows from (4) that $\underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} = E[Z]/\hat{\pi}_1(Y,Y;0,E[Z]) < E[Z]/\pi$. For $\lambda \in [\underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}, \bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}})$, illustrated in panel b, if 1 learns that 2 used the *same* technology, he continues his initial technology irrespective of its value y, $\bar{t}_{\mathsf{S}}^* = 0$.

If agents initially used *different* technologies, then for $\lambda \geq \bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}$, 1 sticks to his initial technology Y, irrespective of its value y, and regardless of what 2 reports, $(\bar{t}_{\mathsf{S}}^*, \bar{t}_{\mathsf{D}}^*) = (0,1)$. Then $\hat{\pi}_1(Y,Y;0,1) = \pi$ as continuation of Y does not reveal any information on ability, while $\hat{\pi}_1(Y,Z;0,1) = 0$ is a plausible out-of-equilibrium belief. Hence, $\bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} = 1/\pi$. Panel c illustrates the reputational gap and the threshold values for the uniform distribution and $\pi = 1/2$. The reputional gap rises for $\lambda < \underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}$ to $\hat{\pi}_1(Y,Y;0,E[Z]) > \pi$, and declines to π for $\underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} < \lambda \leq \bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}}$.

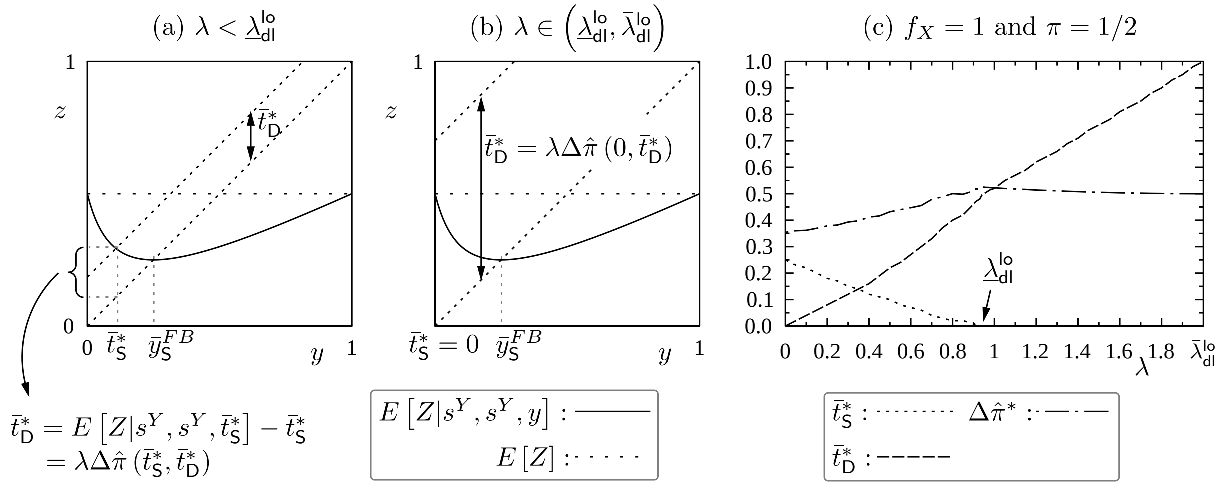


Figure 2: Decentralized learning and local markets. Panels a and b depict the structure of equilibrium. Panel c reports equilibrium threshold values and the reputational gap for the uniform distribution and $\pi = 1/2$. Hence, $\underline{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} < 1$ and $\bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} = 2$.

5.2 Global markets

We start by showing that first-best behaviour, described on page 15, is not equilibrium behaviour. Suppose imputed equilibrium behaviour is first-best behaviour. Then, if agents initially adopted different technologies, the only adoption vectors possible are (Y, Z, Y, Y) and (Y, Z, Z, Z). The inference the market draws from the first (resp. second) vector is that Y (resp. Z) is the superior technology, and that 1 made the correct (resp. wrong) choice. The correct choice can be thanks to skill, or due to low ability and luck. The wrong choice, by contrast, *must* be due to low ability. Hence[21], $\hat{\pi}_1(Y, Z, Y, Y) = \frac{2\pi}{1+\pi} > \pi$ and $\hat{\pi}_1(Y, Z, Z, Z) = 0$. Clearly, from a reputational point of view, the former is the best and the latter is the worst that could happen to agent 1. Could 1 convince 2 to adopt "his" technology? Rather than truthful revelation, consider the following deviation strategy in case of different initial technologies: "send $m_1 = 1$ independent of y, and in the decision stage stick to Y if and only if $y \geq m_2$." The effect of this deviation strategy is that 1 convinces 2 to adopt Y in $t = 2$. Whether 1 continues with Y depends on the reported value m_2 and y. For $y \geq m_2$, the adoption vector in $t = 2$ becomes (Y, Z, Y, Y), the same as it

[21] See the proof of Proposition 3.

would have been had 1 stuck to truthful revelation. If $y < m_2$, the adoption vector in case of the deviation strategy equals (Y, Z, Z, Y), whereas in case of truthful revelation it would have been (Y, Z, Z, Z). The reputation implied by such a deviation is not determined by the imputed equilibrium behaviour. However, it is consistent with the model to assume that, given any adoption vector, any increase in the use at $t = 2$ of the technology 1 adopted in $t = 1$ does not decreases the reputation of 1.

Assumption 1 *Consider any adoption vector with $X_{1,1} = Y$. The reputation of 1 does not decrease if 1 (resp. 2) changes from $X_{1,2} = Z$ to $X_{1,2} = Y$ (resp. from $X_{2,2} = Z$ to $X_{2,2} = Y$).*

With this assumption, the deviation is advantageous in terms of reputation, and costless in terms of technical adequacy. We have proved the next Lemma.

Lemma 2 *First-best behaviour is not equilibrium behaviour in case of decentralized learning with global markets.*

The above line of reasoning can be applied to *any* imputed equilibrium in which, in case agents started by adopting *different* technologies, 2's decision regarding $X_{2,2}$ depends on the message m_1 of 1. The profitable deviation is then for 1 to send the message that induces 2 to adopt Y, and to continue to base his own decision for $t = 2$ on a comparison of y and the expected value of Z given m_2. This shows that the unique equilibrium communication strategy in case $X_{2,1} = Z$ is a pooling strategy.[22] The interest an agent has to convince the other to agent to switch technology destroys all meaningful communication. This is in line with one of the concerns expressed about the OMC in the EU, a case of a decentralized learning process with global markets.

In case agents initially adopted the *same* technology, Y, it is easy to see that truthful revelation is an equilibrium strategy. Communication is also irrelevant.[23] Proposition 3

[22] To avoid a discussion of out-of-equilibrium beliefs, we assume that each agent uses a probability distribution over the full support $[0, 1]$ that is independent of the value y he observed. We refer to this equilibrium communication strategy simply by "pooling strategy".

[23] This is so as in our model technologies have a common value that is learned before agents communicate in $t = 2$.

below establishes that in this case an agent wants to deviate from first-best behaviour in the *decision* stage.

As communication breaks down in case of different initial technologies, and is irrelevant in case of the same initial technology, the equilibrium decision strategy of 1 amounts to a comparison of y with a cut-off value that depends on the number of agents that used the same technology in $t = 1$. Let a *double-cut-off strategy* with cut-offs $(\bar{c}_{\mathsf{S}}, \bar{c}_{\mathsf{D}}) \geqq 0$ be defined as

$$d_1^{\mathsf{dl}}\left(I_1^{\mathsf{dl}}; \bar{c}_{\mathsf{S}}, \bar{c}_{\mathsf{D}}\right) = \begin{cases} Y & \text{if } X_{2,1} = Y \text{ and } y \geq \bar{c}_{\mathsf{S}} \\ Y & \text{if } X_{2,1} = Z \text{ and } y \geq \bar{c}_{\mathsf{D}} \\ Z & \text{otherwise.} \end{cases}$$

Of course, conditional on the information exchanged, the values of $\bar{c}_{\mathsf{S}}$ and $\bar{c}_{\mathsf{D}}$ that would maximize the technological value are $\bar{c}_{\mathsf{S}} = \bar{y}_{\mathsf{S}}^{FB}$, and $\bar{c}_{\mathsf{D}} = E[Z]$.[24] The next Proposition describes equilibrium behaviour.[25]

Proposition 3 *Define* $\underline{\lambda}_{\mathsf{dl}}^{\mathsf{gl}} = E[Z]\frac{1+\pi^2}{\pi(1+\pi)}$ *and* $\bar{\lambda}_{\mathsf{dl}}^{\mathsf{gl}} = E[Z]\frac{1+\pi}{\pi}$. *In case of* decentralized learning *with* global markets, *there exists an equilibrium in which*

(i) the communication strategy is (a) a pooling strategy if initial technologies differ, and (b) truthful revelation if initial technologies are the same;

(ii) the belief function equals (a) the density $f_1\left(z|I_1^{\mathsf{dl}}\right) = f(z)$ *for all* z *and* m_2 *in case* $X_{2,1} = Z$*; and (b) discrete probabilities in case* $X_{2,1} = Y$, $\Pr(y|m_2) = 1$ *for* $y = m_2$ *and* $\Pr(y|m_2) = 0$ *for* $y \neq m_2$*;*

(iii) the decision strategy is a double-cut-off strategy. The cut-off value in case initial technologies are the same, $\bar{c}_{\mathsf{S}}^*$, *satisfies*

$$\lambda\left[\hat{\pi}_1(Y,Y,Y,Y;\bar{c}_{\mathsf{S}}^*) - \hat{\pi}_1(Y,Y,Z,Y)\right] = E\left[Z|s^Y, s^Y, \bar{c}_{\mathsf{S}}^*\right] - \bar{c}_{\mathsf{S}}^*, \tag{6}$$

with $\bar{c}_{\mathsf{S}}^* \in \left(0, \bar{y}_{\mathsf{S}}^{FB}\right)$ *for* $\lambda < \underline{\lambda}_{\mathsf{dl}}^{\mathsf{gl}}$. $\bar{c}_{\mathsf{S}}^*$ *is a decreasing function of* λ.[26] *For* $\lambda \geq \underline{\lambda}_{\mathsf{dl}}^{\mathsf{gl}}$, $\bar{c}_{\mathsf{S}}^* = 0$. *The cut-off value in case initial technologies differ,* $\bar{c}_{\mathsf{D}}^*$, *satisfies*

$$\lambda\frac{\pi}{1+\pi} = E[Z] - \bar{c}_{\mathsf{D}}^*, \tag{7}$$

[24] Note that $E\left[Z|s^Y, s^Z, y\right] = E[Z]$.

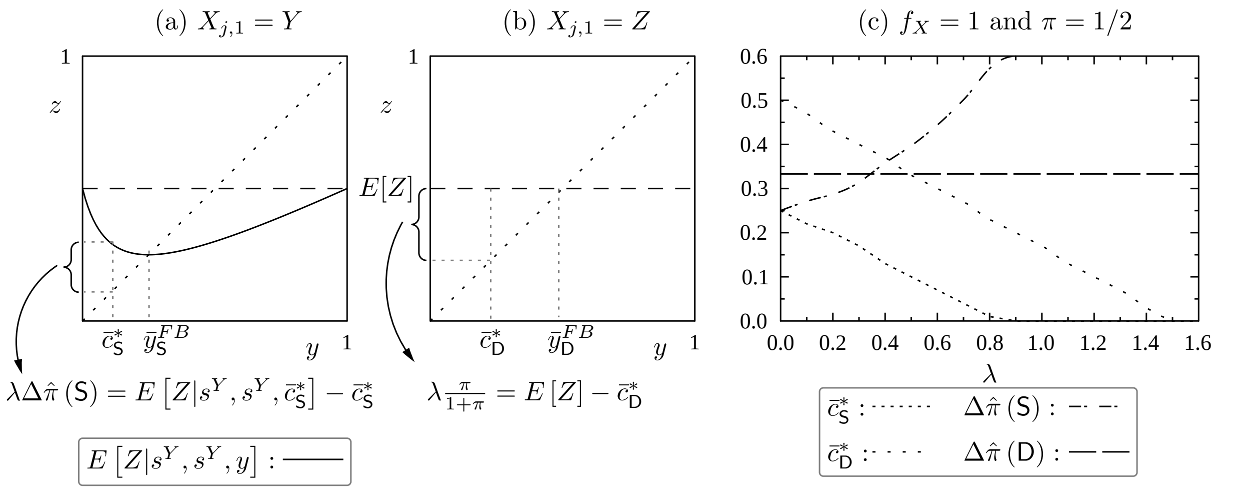
[25] In what follows, we assume that the out-of-equilibrium belief $\hat{\pi}_1(Y,Y,Z,Y)$ equals $\hat{\pi}_1(Y,Y,Z,Z)$.

[26] The remark made in footnote 19 applies.

with $\bar{c}^*_{\mathsf{D}} \in \left(0, \bar{y}^{FB}_{\mathsf{D}}\right)$ *for* $\lambda < \bar{\lambda}^{\mathsf{gl}}_{\mathsf{dl}}$*.* $\bar{c}^*_{\mathsf{D}}$ *is a decreasing function of* λ*. For* $\lambda \geq \bar{\lambda}^{\mathsf{gl}}_{\mathsf{dl}}$*,* $\bar{c}^*_{\mathsf{D}} = 0$*.*

Figure 3, panels a and b correspond to (6) and (7), respectively.

Figure 3: Decentralized learning and global markets. Panels a and b depict the structure of equilibrium. Panel c reports equilibrium cut-off values and reputational gaps for $f_X = 1$ and $\pi = 1/2$. $\Delta\hat{\pi}_1(\mathsf{S})$ denotes $\hat{\pi}_1(Y, Y, Y, Y; \bar{c}^*_S) - \hat{\pi}_1(Y, Y, Z, Y)$, and $\Delta\hat{\pi}_1(\mathsf{D}) = \frac{\pi}{1+\pi}$.



Panel c shows the equilibrium values in case of $f_X = 1$ and $\pi = 1/2$. Eq (7) shows that if agents adopted different technologies in $t = 1$, then the reputational gap is a constant function of $\bar{c}^*_{\mathsf{D}}$. To understand why, recall that ability means the ability to identify the better technology. When the market observes that agents initially used different technologies, the agents' choices in $t = 2$ either allow the market to infer who used the better and the worse technology (i.c., (Y, Z, Z, Z) and (Y, Z, Y, Y)) or does not allow the market to infer any information on the relative performance of the technologies (i.c., (Y, Z, Y, Z) and (Y, Z, Z, Y)). The value of $\bar{c}^*_{\mathsf{D}}$ does not provide additional information on an agent's ability. Of course, if the market observes that agents initially adopted the *same* technology, $\hat{\pi}_1(Y, Y, Y, Y; \bar{c}^*_{\mathsf{S}})$ does depend on the cut-off value: the lower is $\bar{c}^*_{\mathsf{S}}$, the lower is the reputation an agent commands in case of continuation.

Global markets know the technologies adopted at either site. Local markets do not have such knowledge. As a result, there is a single reputational gap in case of local markets, see the left-hand sides of (4) and (5) in Proposition 2. In a global market, there are two reputational gaps. In panel c, $\Delta\hat{\pi}_1(\mathsf{S})$ is the reputational gap in case both agents started with Y. Starting with the same technology is a good sign for each agent's ability. Thus, even if λ increases and $\bar{c}^*_{\mathsf{S}}$ goes to zero $\hat{\pi}_1(Y,Y,Y,Y;\bar{c}^*_{\mathsf{S}}) > \pi$. On the other hand, the lower is $\bar{c}^*_{\mathsf{S}}$, the more switching indicates a poor choice in period 1. The net effect is that the gap increases in λ, see the proof.

6 Centralized learning Process

First-best behaviour in the case of a centralized learning process is for each agent to truthfully reveal his private information, and for the center next to pick the technology with the higher, reported or expected, value:

$$d_C\left(I_C;\bar{y}^{FB}_{\mathsf{S}}\right) = \begin{cases} Y,Y & \text{if } X_{2,1}=Y \text{ and } m_1 \geq \bar{y}^{FB}_{\mathsf{S}} \\ Z,Z & \text{if } X_{2,1}=Y \text{ and } m_1 < \bar{y}^{FB}_{\mathsf{S}} \\ Y,Y & \text{if } X_{2,1}=Z \text{ and } m_1 > m_2 \\ Z,Z & \text{otherwise.} \end{cases}$$

We start by showing that first-best behaviour is not equilibrium behaviour in case of centralized learning.

Lemma 3 *Under centralized learning, an equilibrium in which agents truthfully reveal their private information does not exist, neither in case of local nor in case of global markets.*

It suffices to show that agent 1 has an incentive to slightly exaggerate the value of Y in case j adopted a different solution. If agents and planner were to stick to first-best behaviour, then an agent commands a higher reputation if he is allowed to continue with "his" solution than if he is forced to change. With local markets, $\hat{\pi}_1(Y,Y) > \hat{\pi}_1(Y,Z)$, and with global markets $\hat{\pi}_i(Y,Y,Y,Y) > \hat{\pi}_i(Y,Z,Z,Z)$. In either case, assume i deviates by communicating a slightly exaggerated value of his technology, $y+\varepsilon > y$ instead of y, with $\varepsilon > 0$. Conditional on this exaggeration changing the planner's decision i.e., for $z \in (y, y+\varepsilon)$, the benefits equal $\lambda\left[\hat{\pi}_i(Y,Y,Y,Y) - \hat{\pi}_i(Y,Z,Z,Z)\right] > 0$ and are independent of ε, whereas the costs can be made arbitrarily small by reducing the value of ε. This shows that a profitable deviation from first-best behaviour exists.

Of course, in equilibrium an agent cannot "systematically exaggerate" as then the center could simply undo the exaggeration. Instead, as in Crawford and Sobel (1982), in equilibrium information is lost as the agent adds noise to his message: he partitions the space of possible technology values $[0, 1]$ into intervals, and reports only to which interval the value of his technology belongs. That is, he ranks its value, and the number of intervals equals the number of possible ranks.

Let $\mathbf{a}(N) \equiv (a_0(N), \ldots, a_N(N))$ denote a partition of $[0, 1]$ in N intervals, with $0 = a_0(N) < a_1(N) < \cdots < a_N(N) = 1$. Agent 1 is said to use a *partition strategy* to communicate if there exists a tuple $(N, \mathbf{a}(N))$, such that $\mu_1^{\mathsf{p}}\left(m_1 | s^Y, y, X_{2,1}\right)$ is uniform, supported on $[a_r(N), a_{r+1}(N)]$ if $y \in (a_r(N), a_{r+1}(N))$ for $r = 0, \ldots, N-1$.[27] We focus on the highest value of N consistent with incentives. Say that agent 1 sends *influential information* (or that communication is influential) if there are two messages m_1 and m_1' about Y and a message m_2 about Z such that $d_C(m_1, m_2) = Y$ with probability one and $d_C(m_1', m_2) = Z$ with probability smaller than one. That is, the agent uses at least two ranks, $N \geq 2$. To save space, we write $\mathbf{a}$ instead of $\mathbf{a}(N)$ if this does not lead to confusion.

Does an agent truthfully report the value of his technology to the center if the other agent uses the same technology in $t = 1$? Agent i's interest are different from those of the center, but identical to those of the agent j. This offers room for the agents to (tacitly) collude, and to induce the center to choose the technology they deem best. Each can send either of two messages, one such that the center will next decide that the technology is sufficiently good to merit continuation, and one inducing the center to force the agents to switch. Note that collusive behaviour of this sort seems easy to sustain as there is no asymmetric information among the agents.[28] Although this is a partition strategy with $N \leq 2$, to distinguish it from the more general partition strategy in case agents use different technologies, we refer to it

[27] Note that between any two partitions the expert uses a random strategy. This guarantees that in equilibrium any possible message is sent with strictly positive probability. A discussion of out-of-equilibrium beliefs (what should the planner think about the value of a technology if he were to observe a non-equilibrium message?) can thus be avoided.

[28] In a previous version of this paper we show that truthfully revealing information to the center in case agents use the same technology can be part of equilibrium. However, it amounts to playing a weakly dominated strategy, an unlikely candidate to describe agents' behaviour.

as a *collusion strategy*. It is completely characterized by a single value, $\bar{y}_{\mathsf{S}} \in [0,1]$, for which an agent is indifferent between sending one message rather than the other.

Let the center choose the technology that is the better one given the messages of the agents. In case they rank different technologies the same, the center is indifferent and tosses a coin. Even if both agents report on the same technology, the center may still decide to make them switch to the other technology. Formally,

$$d_C(I_C) = \begin{cases} Y, Y & \text{if } X_{2,1} = Y \quad \text{and } E[Y|m_{\min}] \geq E[Z|m_{\min}] \\ Z, Z & \text{if } X_{2,1} = Y \quad \text{and } E[Y|m_{\min}] < E[Z|m_{\min}] \\ Y, Y & \text{if } X_{2,1} = Z \quad \text{and } E[Y|I_C] > E[Z|I_C] \\ Y, Y & \text{if } X_{2,1} = Z \quad \text{and } E[Y|I_C] = E[Z|I_C] \text{ and } \mathsf{coin} = Y \\ Z, Z & \text{otherwise,} \end{cases} \tag{8}$$

where "$\mathsf{coin}= Y$" means that the center flips a fair coin with faces Y and Z, and Y comes up, and where $m_{\min} := \min[m_1, m_2]$ is the lower valued message sent concerning the same technology. The contents of these messages – what they imply concerning the expected value of the technology – are the same if $m_1, m_2 \in [a_{r-1}, a_r)$ and they differ if $m_1 < a_r \leq m_2$ for some r.[29] To state the belief function of the center, define a truncated density as follows: $Tr(x; a_r, a_{r+1}) = g(x) / (F(a_{r+1}) - F(a_r))$, where $g(x) = f(x)$ for $x \in [a_r, a_{r+1}]$ and $g(x) = 0$ everywhere else. The next proposition characterizes equilibrium behaviour.

Proposition 4 *Define* $\bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}} = E[Z] \frac{(3+\pi^2)(1+\pi)}{4\pi^2}$ *and* $\bar{\lambda}_{\mathsf{cl}}^{\mathsf{gl}} = E[Z] \frac{1+\pi^2}{\pi(1+\pi)}$. *In case of centralized learning, there exists an equilibrium in which*
(i) the center's decision strategy is as defined in (8).
(ii) the communication strategy is (a) a partition strategy $(N^*, \mathbf{a}^*)$ *if initial technologies differ, and (b) a collusion strategy* $\bar{y}_{\mathsf{S}}^*$ *if initial technologies are the same;*
(ii) the center's belief function is (a) $f_1(x_{i,1}|I_C) = Tr(x_{i,1}; a_r^*, a_{r+1}^*)$ *for* $m_1^X \in (a_r^*, a_{r+1}^*)$ *for* $r = 0, \ldots, N^*-1$ *if initial technologies differ, and (b)* $f_1(y|I_C) = Tr(y; 0, \bar{y}_{\mathsf{S}}^*)$ *for* $m_1^Y \in [0, \bar{y}_{\mathsf{S}}^*]$

[29] Note that we assume that the planner tosses a coin in case of $X_{2,1} = Z$ and $E[Y|I_C^{\mathsf{cl}}] = E[Z|I_C^{\mathsf{cl}}]$. This ensures harmonisation - sites adopt the same technology in $t = 2$. In a companion paper we analyse the case where both sites can continue with their initial technologies. This has interesting consequences for the nature and quality of communication.

and $f_1(x_{1,1}|I_C) = Tr(y; \bar{y}^*_{\mathsf{S}}, 1)$ *for* $m^Y_1 \in (\bar{y}^*_{\mathsf{S}}, 1]$ *if initial technologies are the same;*

(iii) in case of **local markets***, the partition* $\mathbf{a}^*$ *and the collusion strategy* $\bar{y}^*_{\mathsf{S}} = \bar{y}^{\mathsf{lo}*}_{\mathsf{S}}$ *satisfy*

$$\lambda\left[\hat{\pi}\left(Y,Y;\bar{y}^{\mathsf{lo}*}_{\mathsf{S}},\mathbf{a}^*\right) - \hat{\pi}\left(Y,Z;\bar{y}^{\mathsf{lo}*}_{\mathsf{S}},\mathbf{a}^*\right)\right] = E\left[Z|a^*_{r-1} \le z \le a^*_{r+1}\right] - a^*_r \quad (9)$$

$$\lambda\left[\hat{\pi}\left(Y,Y;\bar{y}^{\mathsf{lo}*}_{\mathsf{S}},\mathbf{a}^*\right) - \hat{\pi}\left(Y,Z;\bar{y}^{\mathsf{lo}*}_{\mathsf{S}},\mathbf{a}^*\right)\right] = E\left[Z|s^Y, s^Y, \bar{y}^{\mathsf{lo}*}_{\mathsf{S}}\right] - \bar{y}^{\mathsf{lo}*}_{\mathsf{S}} \quad (10)$$

for $r = 1, \ldots, N^* - 1$. *For* $\lambda < \bar{\lambda}^{\mathsf{lo}}_{\mathsf{cl}}$, $N^* \ge 2$ *and* $\bar{y}^{\mathsf{lo}*}_{\mathsf{S}} > 0$, *whereas for* $\lambda \ge \bar{\lambda}^{\mathsf{lo}}_{\mathsf{cl}}$, $N^* = 1$ *and* $\bar{y}^{\mathsf{lo}*}_{\mathsf{S}} = 0$. *That is, the agents do not send influential information on* y *and* z *for* $\lambda \ge \bar{\lambda}^{\mathsf{lo}}_{\mathsf{cl}}$.

(iv) in case of **global markets***, the partition* $\mathbf{a}^*$ *satisfies*

$$\lambda\left[\hat{\pi}_1(Y,Z,Y,Y;\mathbf{a}^*) - \hat{\pi}_1(Y,Z,Z,Z;\mathbf{a}^*)\right] = E\left[Z|a^*_{r-1} \le z \le a^*_{r+1}\right] - a^*_r \quad (11)$$

for $r = 1, \ldots, N^* - 1$. *The collusion strategy* $\bar{y}^*_{\mathsf{S}} = \bar{y}^{\mathsf{gl}*}_{\mathsf{S}}$ *satisfies*

$$\lambda\left[\hat{\pi}\left(Y,Y,Y,Y;\bar{y}^{\mathsf{gl}*}_{\mathsf{S}}\right) - \hat{\pi}\left(Y,Y,Z,Z;\bar{y}^{\mathsf{gl}*}_{\mathsf{S}}\right)\right] = E\left[Z|s^Y, s^Y, \bar{y}^{\mathsf{gl}*}_{\mathsf{S}}\right] - \bar{y}^{\mathsf{gl}*}_{\mathsf{S}}. \quad (12)$$

Moreover, for any finite λ, $N^* \ge 2$. *For* $\lambda < \bar{\lambda}^{\mathsf{gl}}_{\mathsf{cl}}$ $\bar{y}^{\mathsf{gl}*}_{\mathsf{S}} > 0$, *whereas for* $\lambda \ge \bar{\lambda}^{\mathsf{gl}}_{\mathsf{cl}}$ $\bar{y}^{\mathsf{gl}*}_{\mathsf{S}} = 0$. *That is, in case agents initially used different strategies, agents send influential information about* y *and* z *for any finite* λ. *If agents initially used the same technology, they do not send influential information about the technology's values for* $\lambda \ge \bar{\lambda}^{\mathsf{gl}}_{\mathsf{cl}}$.

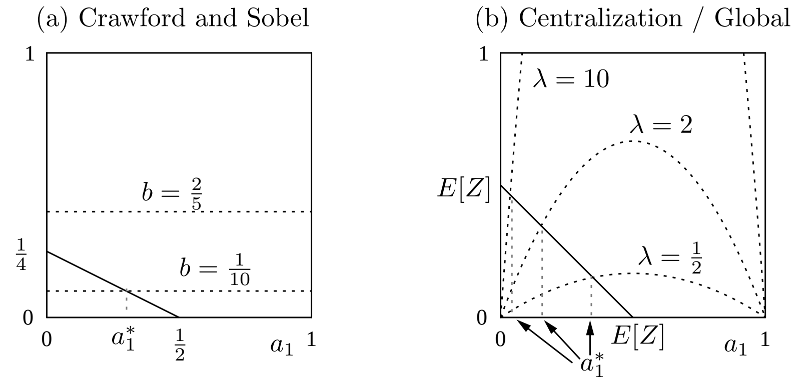
In case agents used different technologies, the communication strategy is a partition strategy. Eqs (9) and (11) determine the partitioning in case of local and global markets, respectively. If agent 1 observes a value y he has to decide how to rank his technology. The higher the rank is, the more likely it becomes that the center chooses his technology. This suggests that his technology is the better one. As a result, agent 1 enjoys a reputational benefit. Ranking it highly also has a cost. If $z > y$ but agent 2 does not rank Z as highly as 1 ranks Y, the center forces both agents to choose Y, the inferior technology in period 2. This possibility stops the agent from ranking his technology too highly. The left-hand sides of the equations state the net reputational value of continuing with one's technology. For $y = a^*_r$, this gain is exactly offset by a loss in expected project value due to continuation: the agent is indifferent between using two adjacent ranks (messages) to describe the value of technology Y. Sending one message rather than the other changes the choice of the center only for $z \in \left(a^*_{r-1}, a^*_{r+1}\right)$, see the right-hand side of (9) and (11).

In terms of informativeness, a partition strategy is in between the truthful revelation that characterizes communication among decentralized agents in a local market and the absence of communication in case decentralized agents operate in global markets. That is, as a result of the move from decentralized learning to centralized learning communication deteriorates in case of local markets but improves in the presence of global markets. In a *local* market the loss of an agent's decision-making power and its uploading to the center means that an agent starts to use his communication to indirectly influence the perception of the market of his ability. The quality of communication drops. In case of a *global* market the loss of decision-making power makes that an agent becomes cautious when communicating: given the communication strategy of the other agent, his own exaggerated claims are no longer costless but can lead to an inferior choice at the agent's own site.

To explain why influential communication among agents and centre remains possible for any finite λ in case of global markets but vanishes for $\lambda \geq \bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}}$ in case of local markets, it is useful to start by comparing the present model with the existing literature that uses cheap talk. As noted in the related literature section, the existing literature focuses on situations in which the difference in preferences between Sender (S, here agent) and Receiver (R, here center) is exogenously given. Consider the leading example introduced by Crawford and Sobel, the uniform quadratic case, in which $U_S(d,y) = -(d-(y+b))^2$ and $U_R(d,y) = -(d-y)^2$ with $y \in [0,1]$ being the state variable that is known to S only, $d \in [0,1]$ the decision that is taken by R. The parameter $b > 0$ captures the difference in preference between S and R. Its exogenously specified value determines the maximum number of intervals (ranks) in the communication strategy of S, and, for a given N, the vector $\mathbf{a}(N)$. In our model, the difference in preference equals $\lambda\hat{\pi}(\cdot)$, where $\hat{\pi}(\cdot)$ is determined in equilibrium. This endogeneity may make that agents send relevant information about the state for any finite λ. Indeed, proposition 4, part iv states that agents send relevant information about the technology's values for any finite λ in case they started out with different technologies and markets are global.

This difference is illustrated in Figure 4. Panel a shows the determination of the equilibrium value a_1^* in the uniform-quadratic case of Crawford and Sobel. For $N = 2$, the value of

Figure 4: Determination of the partition in the communication strategy. Communication limited to at most two ranks. Panel (a) shows the canonical uniform-quadratic case of Crawford and Sobel. Panel (b) shows the case of centralized learning and global markets.



a_1^* solves $a_1 = \frac{1}{2} - 2b$, see e.g. Gibbons (1992, p. 216). This equality can also be written as

$$b = \frac{1}{2}\left(\frac{1}{2} - a_1\right). \tag{13}$$

The LHS captures the difference in preference alignment. It determines the equilibrium value a_1^*. The LHS (RHS) of (13) is plotted as a dotted (drawn) line in panel a. For the Sender to send relevant information $b < 1/4$ must hold.

Panel b shows the determination of the equilibrium value a_1^* in case communication between the agents and center is limited to at most two ranks and markets are global. With at most two ranks, (11) reduces to[30]

$$\lambda \frac{4\pi}{1+\pi} F(a_1)(1 - F(a_1)) = E[Z] - a_1. \tag{14}$$

The dotted lines represent the LHS for various values of λ. The reputational gap, the source of the difference in preference alignment, depends on the equilibrium value a_1^* and equals zero for $a_1 = 0$. The drawn line graphs the RHS. The graphs illustrates that for any finite λ, there is a unique $a_1^* > 0$. That is, for any finite weight λ that the agent puts on his reputation, the agent uses (at least) two ranks.

The key to understand why communication among agents and centre remains possible for any finite λ in case of global markets is the fact that the reputational gap equals zero

[30] See the proof of Proposition 4.

for $a_1 = 0$. If agents use different technologies and $a_1 = 0$, the center decides on the technology that is to be used in $t = 2$ by tossing a coin. As global markets know that the initial distribution of technologies equaled Y, Z, the decision of the center does not add any information on the relative values of the technologies nor on the ability of the agents. Hence, $\hat{\pi}_1(Y, Z, Y, Y; a_1 = 0) = \hat{\pi}_1(Y, Z, Z, Z; a_1 = 0)$. Instead, with *local* markets, relevant communication about the value of a technology is not possible for $\lambda \geq \bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}}$ as even for $a_1 = 0$ (i.e., one rank only) and $\bar{y}_{\mathsf{S}}^{\mathsf{lo}*} = 0$ the reputational gap does not vanish but equals $\frac{4\pi^2}{(3+\pi^2)(1+\pi)}$.[31] The reason is that a local market does not know whether agents initially used the same technologies or different ones. If an agent is forced to change technology, the market deduces that agents must initially have used different technologies and that next the center tossed a coin. The deduced difference in initial technology hurts an agent's reputation. If instead an agent must continue his initial technology this may also mean that both agents initially used the same technology. The latter makes it more likely that the agents received a correct signal. As a result, continuation boosts an agent's reputation, and the reputational gap continues to exist even for $a_1 = 0$.

7 Welfare Comparisons

How does globalization affect the quality of learning? An isolated agent can only learn from his own past experience with a given technology. Globalization allows him to compare his experience with that of others. Furthermore, globalization may make that local markets become global. To understand the welfare consequences of these two forms of globalization, we consider for each process the expected value of the technology that is in use at site 1 in period 2, assuming that 1 starts with Y, $E\left[X_{i,2}|s^Y, \lambda, \pi\right]$. The expectation is taken over y, and before 1 knows agent 2's technology in period 1, assuming of course equilibrium behaviour. The theoretical maximum value is $E[Y|y > z]$, which obtains if agent 1 chooses the better technology in period 2 with probability one. No process generates this value, unless $\pi = 1$ in which case the better technology is identified in $t = 1$. Absent perverse behaviour, the theoretical minimum value is $\pi E[Y|y > z] + (1 - \pi) E[Y]$. This is the expected value in

[31] For the derivation, see the proof of Proposition 4.

case the technology adopted at site 1 in $t = 2$ equals the first period choice with probability one, independent of the experience gained with the technologies in $t = 1$ throughout the economy.

To focus on differences in value creation thanks to learning from own past behaviour and from the experience of others, we transform $E\left[X_{i,2}|s^Y, \lambda, \pi\right]$ using the following formula,

$$W(\lambda, \pi) = \frac{E\left[X_{i,2}|s^Y, \lambda, \pi\right] - (\pi E[Y|y > z] + (1 - \pi) E[Y])}{E[Y|y > z] - (\pi E[Y|y > z] + (1 - \pi) E[Y])} * 100\%. \tag{15}$$

That is, $W(\lambda, \pi) \in [0\%, 100\%]$ captures value creation thanks to learning, over and above the minimum value, as a percentage of what is maximally attainable. We refer to it as 'welfare.'

7.1 Decentralized learning: welfare comparisons

In this subsection, we compare isolated agents with decentralized learning, and decentralized learning cum local markets with decentralized learning cum global markets. A shift from local markets to global markets could be the result of the IT revolution and increased information dissemination over the WWW, or of societal pressures to increase transparency that allow for comparisons across sites.

Key to welfare comparisons are (i) the information agents have, and (ii) the degree to which they use it in the various situations. Consider (i). By definition, an isolated agent only knows the value of his own technology, and does not know what technology has been adopted at the other site. We know from Propositions 2 and 3 that in case of a decentralized learning process for any $\lambda > 0$ agent 1 in a global market also knows $X_{2,1}$ (but not $x_{2,1}$ if $X_{2,1} = Z$), and that with local markets he knows both $X_{2,1}$ and $x_{2,1}$. If an agent does not care about his reputation, additional information can only lead to an increase in welfare. This implies that there is some $\lambda_1 > 0$ such that for all $\lambda \in (0, \lambda_1)$ additional information is also welfare-enhancing: $W_{\mathsf{ia}}(\lambda, \pi) < W_{\mathsf{dl}}^{\mathsf{gl}}(\lambda, \pi) < W_{\mathsf{dl}}^{\mathsf{lo}}(\lambda, \pi)$.

Consider (ii). Propositions 1–3 show that the degree to which information is used depends on the strength of reputational concerns. In particular, they establish for the three cases the values of λ above which an agent ignores all information and simply continues with his initial choice of technology. These values are $\bar{\lambda}_{\mathsf{ia}} = E[Z]/\pi$, $\bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} = 1/\pi$, and $\bar{\lambda}_{\mathsf{dl}}^{\mathsf{gl}} = E[Z](1 + \pi)/\pi$

for an isolated agent, an agent under decentralization and local markets, and an agent under decentralization and global markets, respectively. As $\bar{\lambda}_{\mathsf{ia}} < \bar{\lambda}^{\mathsf{lo}}_{\mathsf{dl}}, \bar{\lambda}^{\mathsf{gl}}_{\mathsf{dl}}$, an isolated agent stops using information for a lower value of λ than a decentralized agent.[32] Furthermore, $\bar{\lambda}^{\mathsf{gl}}_{\mathsf{dl}} < \bar{\lambda}^{\mathsf{lo}}_{\mathsf{dl}}$ if and only if $E[Z](1+\pi) < 1$. If this inequality holds, the ordering for sufficiently high values of λ, $\lambda > \lambda_2$ for some $\lambda_2 > 0$,[33] is the same as for low values of λ: decentralization and local markets leads to the highest project value, next comes decentralized learning with global markets, and isolated agents perform the worst.

To understand the condition $E[Z](1+\pi) < 1$, it is important to realize that information has two roles. On the one hand, additional information helps the *agent* in identifying the better technology. In case of local markets, agent 1 knows the value of the other technology. The difference $z-y$ can be as large as 1. In case of global markets, agent 1 can only calculate $E[Z]-y$. This difference is at most $E[Z]$. Hence, ceteris paribus, λ should be larger in case of local markets than in case of global markets for any information about Z to be ignored and for the agent to continue with Y. On the other hand, additional information helps the *market* in evaluating an agent's ability. A global market knows that agents initially adopted different technologies, whereas a local market does not. As a result, reputation-wise more is at stake in a local market than in a global market. If agent 1 were to continue with Y, rather than to switch to Z, independent of what he knows about Z, then the reputational gap equals π with local markets and $\pi/(1+\pi) < \pi$ with global markets. Hence, ceteris paribus, λ should be larger in case of global markets than in case of local markets for information about Z to be ignored and for the agent to continue with Y. The inequality $E[Z](1+\pi) < 1$ holds if it is sufficiently hard to identify the better technology, and if the unconditional expected value of a technology is sufficiently low. In case of the uniform distribution or any other symmetric distribution it holds as $\pi < 1$.

In Figure 5, we compare project value, measured by W, for decentralized learning with local and global markets and for isolated agents under the assumption that the value of technology $X \in \{Y, Z\}$ is uniformly distributed, $f_X(x) = 1$ on $[0,1]$, and that $\pi = \frac{1}{2}$. [34]

Figure 5 illustrates a number of points. First, learning from one's own past behaviour and from others potentially boosts welfare enormously. For λ close to zero, an isolated agent

[32] Note that the 1 in $\bar{\lambda}^{\mathsf{lo}}_{\mathsf{dl}} = 1/\pi$ is the upperbound of the support of f_X. The inequality therefore holds

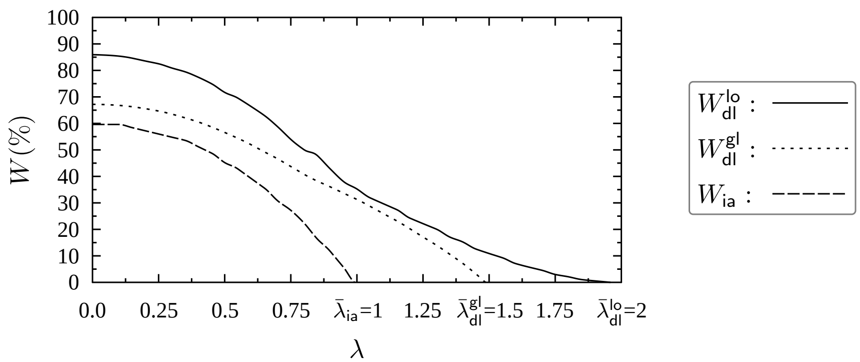


Figure 5: $W(\lambda, \pi)$ for isolated agents and for decentralized learning with local and global markets. $f_X = 1$ and $\pi = 1/2$ such that $\bar{\lambda}_{\mathsf{ia}} = 1$, $\bar{\lambda}^{\mathsf{gl}}_{\mathsf{dl}} = 3/2$, and $\bar{\lambda}^{\mathsf{lo}}_{\mathsf{dl}} = 2$.

who is of high ability with probability $\pi = 1/2$ and learns from his own experience only can capture 60% of the increase in expected project value. Learning from others further increases this percentage. Second, globalization, i.e., global rather than local markets, reduces the positive effect of learning from others. The main reason is that communication breaks down when markets become global. Third, the relative performance does not change in λ. Additional calculations (not reported here) show that this is true independent of the value of π. The following Proposition sums up.[35]

Proposition 5 *For any f_X and π, there exists a $\lambda_1 > 0$ such that $W_{\mathsf{ia}}(\lambda, \pi) < W^{\mathsf{gl}}_{\mathsf{dl}}(\lambda, \pi) < W^{\mathsf{lo}}_{\mathsf{dl}}(\lambda, \pi)$ for all $\lambda < \lambda_1$. Furthermore, for any f_X and π such that $E[Z](1 + \pi) < 1$, there exists a $\lambda_2 > 0$ such that $W_{\mathsf{ia}}(\lambda, \pi) < W^{\mathsf{gl}}_{\mathsf{dl}}(\lambda, \pi) < W^{\mathsf{lo}}_{\mathsf{dl}}(\lambda, \pi)$ for all $\lambda > \lambda_2$. If instead f_X and π satisfy $1 < E[Z](1+\pi)$, then there exists a $\lambda_3 > 0$ such that $W_{\mathsf{ia}}(\lambda, \pi) < W^{\mathsf{lo}}_{\mathsf{dl}}(\lambda, \pi) < W^{\mathsf{gl}}_{\mathsf{dl}}(\lambda, \pi)$ for $\lambda > \lambda_3$. For $f_X = 1$, the uniform distribution, $W_{\mathsf{ia}}(\lambda, \pi) < W^{\mathsf{gl}}_{\mathsf{dl}}(\lambda, \pi) < W^{\mathsf{lo}}_{\mathsf{dl}}(\lambda, \pi)$ holds for all λ and π.*

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independent of the chosen support.

[33]By continuity, $\lambda_2 < \bar{\lambda}^{\mathsf{gl}}_{\mathsf{dl}}$.

[34]For $f_X = 1$ and $\pi = 1/2$, $E[Y|y > z] = 2/3$ and $\pi E[Y|y > z] + (1 - \pi) E[Y] = 7/12$.

[35]If $\lambda \in \left(\bar{\lambda}^{\mathsf{gl}}_{\mathsf{dl}}, \bar{\lambda}^{\mathsf{lo}}_{\mathsf{dl}}\right)$, then $W_{\mathsf{ia}}(\lambda, \pi) = W^{\mathsf{gl}}_{\mathsf{dl}}(\lambda, \pi) = 0 < W^{\mathsf{lo}}_{\mathsf{dl}}(\lambda, \pi)$. If $\lambda \geq \bar{\lambda}^{\mathsf{lo}}_{\mathsf{dl}}$, then, $W_{\mathsf{ia}}(\lambda, \pi) = W^{\mathsf{gl}}_{\mathsf{dl}}(\lambda, \pi) = W^{\mathsf{lo}}_{\mathsf{dl}}(\lambda, \pi) = 0$. These cases are ignored in Proposition 5.

7.2 Centralized learning: welfare comparisons

In this subsection, we compare isolated agents with centralized learning, and centralized learning cum local markets with centralized learning cum global markets. Propositions 1 and 4 allow us to compare welfare W in case of centralized learning and isolated agents.[36]

Proposition 6 *For any f_X and π, there exists a $\lambda_4 > 0$ such that $W_{\mathsf{ia}}(\lambda,\pi) < W_{\mathsf{cl}}^{\mathsf{lo}}(\lambda,\pi), W_{\mathsf{cl}}^{\mathsf{gl}}(\lambda,\pi)$ for all $\lambda \in (0,\lambda_4)$. Furthermore, for any f_X and π there exists a $\lambda_5 > 0$ such that $W_{\mathsf{ia}}(\lambda,\pi) < W_{\mathsf{cl}}^{\mathsf{lo}}(\lambda,\pi) < W_{\mathsf{cl}}^{\mathsf{gl}}(\lambda,\pi)$ for all $\lambda > \lambda_5$. In addition, for $f_X = 1$, the uniform distribution, $W_{\mathsf{ia}}(\lambda,\pi) < W_{\mathsf{cl}}^{\mathsf{gl}}(\lambda,\pi), W_{\mathsf{cl}}^{\mathsf{lo}}(\lambda,\pi)$ holds for all $\lambda > 0$ and π.*

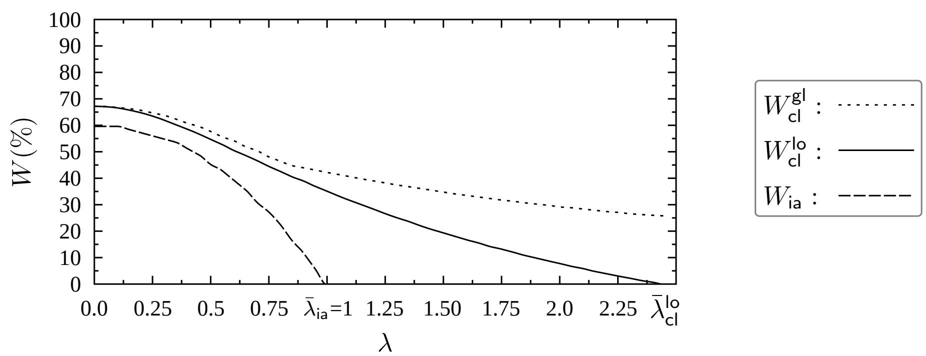

Figure 6: $W(\lambda,\pi)$ for isolated agents and for centralized learning with local and global markets. $W(\lambda,\pi)$ in case of centralized learning is based on a partition strategy with at most two ranks. $f_X = 1$ and $\pi = 1/2$, such that $\bar{\lambda}_{\mathsf{ia}} = 1$, $\bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}} = 2\frac{7}{16}$.

Proposition 6 is illustrated in Figure 6 for the uniform distribution and $\pi = 1/2$. We have imposed that communication with the center is limited to at most two ranks in case agents initially used different technologies. Clearly, if agents can learn from others welfare improves. Because of our limitation to at most two ranks, the graph understates the benefits for low values of λ. In fact, for $\lambda = 0$, agents would truthfully reveal their private information and the performance of a centralized learning process would equal that of a decentralized learning process. We then know from Figure 5 that $W \approx 86\%$ rather than $W \approx 68\%$ as shown in the graph. Note that when markets become global the positive effect of learning

[36] If $\lambda \geq \bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}}$, then, $W_{\mathsf{ia}}(\lambda,\pi) = W_{\mathsf{cl}}^{\mathsf{lo}}(\lambda,\pi) = 0$. This case is ignored in Proposition 6.

from others further increases, especially for high values of λ. This stems from the fact that communication between agents and center remains influential for any finite λ in case of global markets, whereas it dies out for high values of λ in case of local markets.

7.3 What learning process is best for given markets?

The welfare comparisons in the previous two subsections show how a given learning process fares under different degrees of market globalization. In this subsection we turn to the complementary question, and analyse, for a given degree of globalization of markets, the conditions that determine whether decentralization or centralization performs best.

If markets are local, the learning process that is best depends fundamentally on the parameters of the model.[37]

Proposition 7 *In case of* local markets, *there exists a* $\lambda_6 < \bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}}$ *such that welfare* $W(\lambda, \pi)$ *is higher with* decentralized learning *than with* centralized learning *for all* $\lambda > \lambda_6$ *if and only if*

$$\frac{1}{E[Z]} > \frac{(3+\pi^2)(1+\pi)}{4\pi}. \tag{16}$$

If condition (16) is met, there are values of λ such that under decentralization the technology adoption decision in $t = 2$ depends on the observed values y and z, whereas in a centralized process, agents do not transmit useful information about their technologies. As a result, expected welfare is higher in case of decentralized learning.

Note that $(3+\pi^2)(1+\pi)/4\pi > 2$ for all π. $1/E[Z]$ is the ratio of the upperbound of the support and the expected value of the technology. Hence, the ratio should exceed 2 for there to be values of π such that decentralization outperforms centralization for high values of λ. The uniform distribution cannot meet this condition. Does this mean that welfare is higher under centralization than under decentralization in case of the uniform distribution for *all* λ and π? The next proposition provides sufficient conditions on λ and π such that decentralization outperforms centralization.

[37] If $\lambda \geq \bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}}$, then $W_{\mathsf{dl}}^{\mathsf{lo}}(\lambda, \pi) = W_{\mathsf{cl}}^{\mathsf{lo}}(\lambda, \pi)$. This case is ignored in Proposition 7.

Proposition 8 *Assume local markets and technology values that are uniformly distributed. Then, for any π there are values of λ, $\lambda \in \left[\underline{\lambda}(\pi), \bar{\lambda}(\pi)\right]$, with $0 < \underline{\lambda}(\pi) < \bar{\lambda}(\pi)$, such that welfare $W(\lambda, \pi)$ is higher under decentralized learning than under centralized learning.*

What learning process is best if markets are global?

Proposition 9 *In case of global markets, and for any f_X, π, and λ, welfare $W(\lambda, \pi)$ is higher with centralized learning than with decentralized learning.*

The main benefit of moving from decentralization to centralization in case of global markets is the restoration of communication when agents initially used different technologies. The proof establishes that even if agents in a centralized learning process were to limit themselves to a communication strategy consisting of at most two ranks - and choose a_1^* optimally - welfare goes up. This suggests that the welfare difference can be substantial for low values of λ, as such values allow for richer communication (i.e., finer partitions).

8 Concluding Remarks

An important objective of this paper was to gain insight into the effects of alternative learning processes on the quality of decisions in situations where information is dispersed among agents, and agents are concerned about their reputations. Our analysis focuses on two broad features of decision-making processes: the extent of centralization and whether decision-makers operate in a local or global world. We believe that our focus enabled us to derive a couple of interesting results. By focusing on these two broad features, we have abstracted from other features of decision-making processes. Here we would like to elaborate on some of the specific assumptions we have made.

Centralization. One important assumption is that in a centralized process the center always acts in the general interest. In reality, there is little reason to put so much confidence in central bodies. For example, a center may be biased towards one of the technologies because of favoritism. Alternatively, a center may be biased because somehow its name is connected to one of the technologies. Of course, our assumption of a "benevolent" center provides too favourable a picture of centralized processes.

Information. We have described the private information that agents have as non-verifiable, and communication as cheap talk. Although this may well reflect an important part of information agents have gained locally, they may also have verifiable information. Such information can be checked by other agents. If it is unknown whether an agent actually possesses information that is decision-relevant to another agent, the former may have an incentive to selectively withhold his private information from the latter, see e.g. Milgrom and Roberts (1986). How does the presence of verifiable information change our findings? Although the nature of information manipulation changes, the incentives to manipulate continue to be determined by the interplay of the decision rights and the knowledge the markets have. As a result, the quality of information exchange depends in essentially the same way on these same two factors. Consider decentralized decision-making with local markets. The fact that an agent's reputation is independent of what the other agent does and that an agent can decide himself what technology he uses next makes that revealing all positive and negative pieces of information is a weakly dominant strategy. With global markets (and decentralised decision-making), it is important from a reputational perspective to convince the other agent to switch to "your" technology. As a result, any negative information will be withheld. The introduction of centralised decision-making in the presence of global markets gives rise to the selective revelation of negative information. On the one hand, as the agent at a site loses decision-making power, he wants to make sure that the center is well-informed. On the other hand, his reputational concerns imply that he wants the center to impose "his" technology at either site. Ceteris paribus, the more damaging negative information is for the technological value, the more likely it is that the information is revealed. Similarly, the more damaging negative information is for his reputation, the less likely it becomes that this information is revealed.

In our model, signals are for free. However, one can easily imagine situations where agents can increase the probability of receiving an informative signal by putting more effort in investigating technologies. We consider modeling agents' effort decisions as a promising extension of our model. We expect that reputational concerns do not only lead to distortions in communication and decisions, but that they may also induce agents to put more effort in investigating technologies, see e.g. Suurmond et al. (2004).

Decision rights. We have limited attention to centralization and decentralization. A possible third organizational structure is a committee consisting of the two agents that makes a collective decision in period 2 on the basis of some voting rule. Visser and Swank (2007) analyze communication and voting in committees in the presence of reputational concerns.

Our approach is particularly relevant for situations where agents independently gained experiences that are worth sharing. In our model, period 1 represents history. However, in other situations experience still has to be gained. Then, some planner could opt for ignoring signals and assign one technology to agent 1 and the other technology to agent 2. Such a procedure is likely to weaken reputational concerns as the technology decisions are no longer linked to signals. Moreover, it allows for learning in period 2. It is easy to show that assigning technologies in period 1 is optimal if signals are not very informative. The first-period costs of ignoring signals are then small.

9 Appendix

We use the abbreviations ia, dl, cl, gl, and lo to refer to specific learning processes and degrees of market globalization. Recall that $F_X\left(x|s^X,\bar{\theta}\right)=F\left(x\right)^2$, and $F_X\left(x|s^X,\underline{\theta}\right)=F\left(x\right)$.

Proof of lemma 1: Consider (1) in the text. (a) As $\Pr\left(\bar{\theta}|s^Y,0\right)=0$, $E\left[Z|s^Y,0\right]=E\left[Z\right]$. Similarly, as $\Pr\left(\bar{\theta}|s^Y,1\right)=1$, then $E\left[Z|s^Y,1,\bar{\theta}\right]=E\left[Z\right]$, and therefore $E\left[Z|s^Y,1\right]=E\left[Z\right]$. Moreover, $E\left[Z|s^Y,y,\bar{\theta}\right]<E\left[Z\right]$ for $y\in(0,1)$, as the term on the LHS is the expected value of the truncated distribution on $[0,y)$. (b) To determine the derivative, use Bayes' rule to write $\Pr\left(\bar{\theta}|s^Y,y\right)=2F\left(y\right)\pi/\left(2F\left(y\right)\pi+(1-\pi)\right)$. Also, $E\left[Z|s^Y,y,\bar{\theta}\right]=\int_0^y tf\left(t\right)dt/F\left(y\right)$. One can verify that $\partial\Pr\left(\bar{\theta}|s^Y,y\right)/\partial y=\Pr\left(\bar{\theta}|s^Y,y\right)\left(1-\Pr\left(\bar{\theta}|s^Y,y\right)\right)\frac{f(y)}{F(y)}>0$, and that $\partial E\left[Z|s^Y,y,\bar{\theta}\right]/\partial y=\left(y-E\left[Z|s^Y,y,\bar{\theta}\right]\right)\frac{f(y)}{F(y)}$. Hence,

$$\partial E\left[Z|s^Y,y\right]/\partial y=\Pr\left(\bar{\theta}|s^Y,y\right)\frac{f\left(y\right)}{F\left(y\right)}\left(y-E\left[Z|s^Y,y\right]\right),$$

from which it follows immediately that $E\left[Z|s^Y,y\right]$ is decreasing for $y<E\left[Z|s^Y,y\right]$ and increasing for $y>E\left[Z|s^Y,y\right]$. Hence, $y=E\left[Z|s^Y,y\right]$ has a unique solution. ■

Proof of Proposition 1: First, $\hat{\pi}\left(YY;\bar{t}\right)=\Pr\left(\bar{\theta}|YY;\bar{t}\right)$ in (2). Use $\Pr\left(YY|\bar{\theta}\right)=\Pr\left(y\geq\bar{t}|\bar{\theta}\right)/2=\left(1-F\left(\bar{t}\right)^2\right)/2$ and $\Pr\left(YY|\underline{\theta}\right)=\Pr\left(y\geq\bar{t}|\underline{\theta}\right)/2=\left(1-F\left(\bar{t}\right)\right)/2$, and apply Bayes rule (analogously for $\hat{\pi}(YZ;\bar{t})$. Clearly, for given reputations the equilibrium strategy is a single threshold strategy with $\bar{y}^*_{\mathsf{ia}}$ satisfying (3). Given this strategy, equilibrium reputations are as in (2) with $\bar{t} = \bar{y}^*_{\mathsf{ia}}$. To see that $\bar{y}^*_{\mathsf{ia}}$ is a decreasing function of λ for $\lambda \leq \bar{\lambda}_{\mathsf{ia}}$. Define $\delta := \bar{y}^{FB}_{\mathsf{ia}} - \bar{y}_{\mathsf{ia}}$ and $\Delta\hat{\pi} := \hat{\pi}(YY) - \hat{\pi}(YZ)$. Then $(\delta, \Delta\hat{\pi}) \in L := [0, E[Z]] \times [0,1]$, and so L is a complete lattice. It follows from Lemma 1 that (3) can be written as $\delta = f_1(\Delta\hat{\pi}, \lambda)$. It follows from (3) that the function f_1 satisfies $\partial f_1/\partial\Delta\hat{\pi}, \partial f_1/\partial\lambda > 0$, and from (2) that $\Delta\hat{\pi} = f_2(\delta)$ is an increasing function of δ. Hence, we can apply Theorem 3 in Milgrom and Roberts (1994). The set of fixed points of $f : L \times \mathbb{R}^+ \to L$ is non-empty and equals the set of equilibria, and $\delta^* = \bar{y}^{FB}_{\mathsf{ia}} - \bar{y}^*_{\mathsf{ia}}$ is increasing in λ. Moreover, in case this set is not a singleton, both the highest and the lowest fixed point are increasing in λ. It is straightforward to check that for $\lambda \geq \bar{\lambda}_{\mathsf{ia}}$, $\bar{y}^*_{\mathsf{ia}} = 0$.■

Proof of Proposition 2: The equilibrium belief functions follow immediately from the equilibrium message strategies. That the decision strategy is a double-threshold strategy follows from the analysis preceding the statement of the proposition. Finally, note that for $\bar{t}^*_{\mathsf{S}} = 0$, the RHS of (4) equals $E[Z]$, and therefore $\bar{t}^*_{\mathsf{D}} = E[Z]$, and thus $\lambda = \underline{\lambda}^{\mathsf{lo}}_{\mathsf{dl}}$. Finally, if $\bar{t}^*_{\mathsf{S}} = 0$ and $\bar{t}^*_{\mathsf{D}} = 1$, $\hat{\pi}(YY;0,1) = \pi$ (as agent uses pooling strategy) and $\hat{\pi}(YZ;0,1) = 0$ (this is an out-of-equilibrium belief, the limit of $\hat{\pi}(YZ)$ in case $\bar{t}^*_{\mathsf{D}} \uparrow 1$) such that for $\lambda \geq \bar{\lambda}^{\mathsf{lo}}_{\mathsf{dl}}$, the agents indeed continue with their initial technologies no matter what.■

Proof of Proposition 3: First, the reputations. $\hat{\pi}_1(YYYY;\bar{c}) = \Pr\left(\bar{\theta}|YYYY;\bar{c}\right)$. Write $F(\bar{c}) = F$. Use $\Pr\left(YYYY|\bar{\theta}\right) = \Pr\left(YYYY|\bar{\theta}, y > z\right)/2 = (1+\pi)\Pr(y > \bar{c}|y > z)/4 = (1+\pi)(1-F^2)/4$ and $\Pr(YYYY|\underline{\theta}) = (1+\pi)(1-F^2)/8 + (1-\pi)(1-F)^2/8$, and so $\hat{\pi}(YYYY;\bar{c}) = (1+F)\frac{1+\pi}{1+\pi^2+2F\pi}\pi > \pi$. Similarly, $\hat{\pi}(YYZZ;\bar{c}) = F\frac{\pi+1}{1+\pi(2F-2+\pi)}\pi$. One can check that $\Delta\hat{\pi}(\mathsf{S}) := \hat{\pi}(YYYY;\bar{c}) - \hat{\pi}(YYZZ;\bar{c})$ is decreasing in $\bar{c}$. In particular, for $\bar{c}^*_{\mathsf{S}} = 0$, the gap equals $\frac{1+\pi}{1+\pi^2}\pi$. Also, $\hat{\pi}_1(YZYY) = \Pr\left(\bar{\theta}|YZYY\right)$. From $\{Y,Z,Y,Y\}$ the market deduces that $y > z$ in case of both first-best and equilibrium behaviour. Thus, $\Pr\left(YZYY|\bar{\theta}\right) = (1-\pi)/4$ (as $\theta_2 = \underline{\theta}$ for $X_{2,1} = Z$) and $\Pr(YZYY|\underline{\theta}) = (1-\pi)/8$, and apply Bayes rule. Finally, $\hat{\pi}_1(YZYZ) = \Pr\left(\bar{\theta}|YZYZ\right)$. From $\{Y,Z,Y,Z\}$ the market deduces that $(y,z) \in A := \{(y,z)\,|y,z < \bar{c}^*_{\mathsf{D}} \text{ or } y,z > \bar{c}^*_{\mathsf{D}}\}$. Use $\Pr\left(YZYZ|\bar{\theta}\right) = \frac{1-\pi}{2}\Pr(A|y > z)\frac{1}{2}$, $\Pr(YZYZ|\underline{\theta}) = \frac{1}{2}\frac{1-\pi}{2}\Pr(A|y > z)\frac{1}{2} + \frac{1}{2}\frac{1+\pi}{2}\Pr(A|z > y)\frac{1}{2}$, and $\Pr(A|z > y) = \Pr(A|y > z)$ (as Y and Z are iid), and apply Bayes rule. For given reputations and behaviour of 2, if

$y=\bar{c}^*_{\mathsf{D}}$, and if 1 continues Y he gets $\bar{c}^*_{\mathsf{D}}+\lambda\Pr\left(z<\bar{c}^*_{\mathsf{D}}\right)2\pi/\left(1+\pi\right)+\lambda\Pr\left(z\geq\bar{c}^*_{\mathsf{D}}\right)\pi/\left(1+\pi\right)$, whereas switching to Z yields $E\left[Z\right]+\lambda\Pr\left(z<\bar{c}^*_{\mathsf{D}}\right)\pi/\left(1+\pi\right)$. Equating these expressions, one obtains (7). It is immediate that $\bar{c}^*_{\mathsf{D}}$ is a decreasing function of λ. The comparative statics result on $\bar{c}^*_{\mathsf{S}}$ uses Theorem 3 in Milgrom and Roberts (1994), see also proof of Proposition 1. The expressions for $\underline{\lambda}^{\mathsf{gl}}_{\mathsf{dl}}$ and $\bar{\lambda}^{\mathsf{gl}}_{\mathsf{dl}}$ are then immediate.■

Proof of Proposition 4: Assume $X_{1,1}\neq X_{2,1}$, that the center uses (8), that reputations are given, and that agent 2 uses the partition strategy $\left(N^*,\mathbf{a}^*\right)$ to communicate about Z. We show that it is then a best-reply for agent 1 to use a partition strategy with the same partitions to communicate about Y. We focus on the case of lo, and write $\hat{\pi}\left(Y,X\right)$ instead of $\hat{\pi}\left(Y,X;\bar{y}^{\mathsf{lo}*}_{\mathsf{S}},\mathbf{a}^*\right)$. Derivations for the gl case are analogous. Let $y=a_r$, where we have suppressed reference to the number of partitions N. At this value of y, 1 should be indifferent between sending some $m_{r+1}\in\left[a_r,a_{r+1}\right)$ or some $m_r\in\left[a_{r-1},a_r\right)$. If $z<a_{r-1}$ or $z\geq a_{r+1}$, whether 1 sends m_r or m_{r+1} does not affect the decision of the center. Hence, one can limit attention to $z\in\left[a_{r-1},a_{r+1}\right)$. As $E\left[Z|s^Y,s^Z,y=a_r\right]=E\left[Z\right]$, $E\left[Z|s^Y,s^Z,y=a_r,\alpha\leq z\leq\beta\right]=E\left[Z|\alpha\leq z\leq\beta\right]$ for any pair $\left(\alpha,\beta\right)$ such that $0\leq\alpha<\beta\leq 1$. Let $p\left(\alpha,\beta\right):=F\left(\beta\right)-F\left(\alpha\right)$. Sending m_{r+1} yields agent 1

$$\begin{aligned}&p\left(a_{r-1},a_r\right)\left[a_r+\lambda\hat{\pi}_1\left(YY\right)\right]+\frac{1}{2}p\left(a_r,a_{r+1}\right)\left[a_r+\lambda\hat{\pi}_1\left(YY\right)\right]+\\&\frac{1}{2}p\left(a_r,a_{r+1}\right)\left[E\left[Z|a_r\leq z<a_{r+1}\right]+\lambda\hat{\pi}_1\left(YZ\right)\right],\end{aligned}\tag{17}$$

whereas m_r yields

$$\begin{aligned}&\frac{1}{2}p\left(a_{r-1},a_r\right)\left[a_r+\lambda\hat{\pi}_1\left(YY\right)\right]+\frac{1}{2}p\left(a_{r-1},a_r\right)\left[E\left[Z|a_{r-1}\leq z<a_r\right]+\lambda\hat{\pi}_1\left(YZ\right)\right]\\&+p\left(a_r,a_{r+1}\right)\left[E\left[Z|a_r\leq z<a_{r+1}\right]+\lambda\hat{\pi}_1\left(YZ\right)\right].\end{aligned}\tag{18}$$

Equating (17) and (18) shows that agent 1 is indifferent between sending m_{r+1} and m_r for $y=a_r$ if (9) holds.

If $X_{1,1}=X_{2,1}=Y$, it is straightforward to check that, if agent 2 uses the collusion strategy, if the center's decision strategy is as stated, and for given beliefs $\hat{\pi}$, then for agent 1 a collusion strategy with $\bar{y}^{\mathsf{lo}*}_{\mathsf{S}}$ satisfying (10) is a best-reply. It is straightforward to establish that the belief function follows from applying Bayes' rule to the communication strategies of the agents, and that the center's decision strategy is a best reply given the belief function.

Consider $\bar{y}_S^{\mathsf{lo}*} = 0, \mathbf{a}_1^*(1) = 0$ (a pooling communication strategy). To determine $\hat{\pi}(YY) - \hat{\pi}(YZ)$, use $\Pr\left(YY|\bar{\theta}\right) = \Pr\left(YY|\bar{\theta}, y > z\right)\frac{1}{2} + \Pr\left(YY|\bar{\theta}, z > y\right)\frac{1}{2} = \frac{1}{8}\pi + \frac{3}{8}$, and $\Pr(YY|\underline{\theta}) = \frac{3}{8}$. Hence, $\hat{\pi}(YY) = \frac{3+\pi}{3+\pi^2}\pi$. Similarly, $\hat{\pi}(YZ) = \frac{\pi}{\pi+1}$, such that $\hat{\pi}(YY) - \hat{\pi}(YZ) = \frac{4\pi}{(3+\pi^2)(1+\pi)}\pi$. The RHS of both (9) and (10) become $E[Z]$. Hence, this communication strategy is indeed the equilibrium for $\lambda \geq \bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}}$.

Now turn to gl. Assume $X_{1,1} = X_{2,1} = Y$. For given parameter values the collusion strategy is the same as the cut-off strategy in case of dl cum gl. Thus, $\hat{\pi}\left(YYYY; \bar{y}_{\mathsf{S}}^{\mathsf{gl}*} = 0\right) = (1 + F(0))\frac{1+\pi}{1+\pi^2+2F(0)\pi}\pi = \pi(1+\pi)/(1+\pi^2)$, and $\hat{\pi}\left(YYZZ; \bar{y}_{\mathsf{S}}^{\mathsf{gl}*} = 0\right) = 0$, and the RHS of (12) becomes $E[Z]$ for $\bar{y}_{\mathsf{S}}^{\mathsf{gl}*} = 0$. Hence, this collusion strategy is indeed the equilibrium strategy for $\lambda \geq \bar{\lambda}_{\mathsf{cl}}^{\mathsf{gl}}$.

Now assume $X_{1,1} \neq X_{2,1}$. Assume $N = 2$, and define $a := a_1$. $\hat{\pi}_1(YZYY; a) = \Pr\left(\bar{\theta}|YZYY; a\right)$. Use

$$\begin{aligned}\Pr\left(YZYY|\bar{\theta}; a\right) &= \frac{1}{2}\frac{1-\pi}{2}\left(\Pr(y > a > z|y > z) + \Pr(y > z > a|y > z)\frac{1}{2} + \Pr(a > y > z|y > z)\frac{1}{2}\right) \\ &= \frac{1-\pi}{4}\left(\frac{1}{2} + F(a)(1 - F(a))\right).\end{aligned}$$

Similarly, $\Pr\left(YZYY|\bar{\theta}; a\right) = \frac{1}{8} - \frac{\pi}{4}F(a)(1 - F(a))$. Hence, $\hat{\pi}_1(YZYY) = \frac{\pi}{1+\pi}\left(1 + 2F(a) - 2F(a)^2\right)$. Analogously, $\hat{\pi}_1(YZZZ) = \frac{\pi}{1+\pi}\left(1 - 2F(a) + 2F(a)^2\right)$, and the reputational gap becomes $4\frac{\pi}{1+\pi}F(a)(1 - F(a))$. As $\lambda\frac{4\pi}{1+\pi}F(0)(1 - F(0)) = 0 < E[Z]$ and $\lambda\frac{4\pi}{1+\pi}F(E(Z))(1 - F(E[Z])) > 0$, for all continuous F and any finite λ there is a unique $a_1^* > 0$ that satisfies (11). That is, for any finite λ, $N^* \geq 2$.■

Proof of Proposition 6: Suppose $\lambda = 0$. Then, $W_{\mathsf{ia}}(0, \pi)$ is equal to $W(0, \pi)$ in case *one* agent reports to the center that $y \geq \bar{y}_{\mathsf{ia}}^{FB}$ or $y < \bar{y}_{\mathsf{ia}}^{FB}$. In case of cl, *two* agents reveal information truthfully to the center. By continuity of $W_{\mathsf{ia}}(\lambda, \pi)$ and $W_{\mathsf{cl}}(\lambda, \pi)$ in λ, $W_{\mathsf{ia}}(\lambda, \pi) < W_{\mathsf{cl}}(\lambda, \pi)$ for all $\lambda < \lambda_4$, for some $\lambda_4 > 0$. The second part of the proposition follows from the facts that (i) $\bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}} > \bar{\lambda}_{\mathsf{ia}}$ (see Propositions 1 and 4), and (ii) for all λ agents send influential information under cl *cum* gl. The truth of the final statement in the proposition has been verified numerically.■

Proof of Proposition 7: It follows from Propositions 2 and 4 that $\bar{\lambda}_{\mathsf{dl}}^{\mathsf{lo}} > \bar{\lambda}_{\mathsf{cl}}^{\mathsf{lo}}$ iff (16) holds. The existence of λ_6 then follows from the continuity of W in λ.■

Proof of Proposition 8: Consider cl, and suppose $N = 3$. We know $E[Z|0 = a_0 \leq z \leq a_2] -$

$a_1 = E[Z|a_1 \leq z \leq a_3 = 1] - a_2$ from (9). If two becomes the maximum number of ranks, then $a_1 = 0$, and so this equality becomes $E[Z|0 \leq z \leq a_2] = E[Z] - a_2$. For any f_X, let $a_2^* < E[Z]$ denote the unique value of a_2 satisfying this equality. Let $\mathbf{a}_{2/3}^* := (0, 0, a_2^*, 1)$. Hence, (9) and (10) become $\lambda \left[\hat{\pi}\left(YY; \bar{y}_{\mathsf{S}}^{\mathsf{lo}}, \mathbf{a}_{2/3}^*\right) - \hat{\pi}\left(YZ; \bar{y}_{\mathsf{S}}^{\mathsf{lo}}, \mathbf{a}_{2/3}^*\right)\right] = E[Z] - a_2^*$ and $E\left[Z|s^Y, s^Y, \bar{y}_{\mathsf{S}}^{\mathsf{lo}}\right] - \bar{y}_{\mathsf{S}}^{\mathsf{lo}} = E[Z] - a_2^*$. There is a unique $\bar{y}_{\mathsf{S}}^{\mathsf{lo}}(\pi)$ that satisfies the latter equality. We can then use $\lambda \left[\hat{\pi}\left(YY; \bar{y}_{\mathsf{S}}^{\mathsf{lo}}(\pi), \mathbf{a}_{2/3}^*\right) - \hat{\pi}\left(YZ; \bar{y}_{\mathsf{S}}^{\mathsf{lo}}(\pi), \mathbf{a}_{2/3}^*\right)\right] = E[Z] - a_2^*$ to find $\underline{\lambda}(\pi)$. For $\lambda \geq \underline{\lambda}(\pi)$, agents use at most two ranks. $\bar{\lambda}(\pi)$ is obtained from our numerical simulations. We checked the statement for $\pi \in [0.05, 0.95]$.■

Proof of Proposition 9: Fix λ, π, and f_X. Suppose $X_{1,1} = X_{2,1}$. A straightforward comparison of (6) and (12) shows that welfare is the same under dl and cl for all f_X, π, and λ. Now suppose $X_{1,1} \neq X_{2,1}$. In case of cl and in equilibrium, the more ranks the agents use, the higher is W. Hence, it suffices to show that the proposition is true if communication under cl is limited to two ranks. Proposition 4 *(iv)* shows that an equilibrium with two ranks exists for all parameter values. This partition is characterized by $a_1^* \in (0, E[Z])$. Thus, if agents rank their technologies differently, the center picks the higher ranked technology. Given the communication strategies of the agents this technology is indeed the better one. However, for $(y, z) \in [0, a_1^*]^2$ and $(y, z) \in [a_1^*, 1]^2$, both technologies are ranked in the same way. Hence, the center tosses a fair coin. The inferior technology is chosen half of the time at both sites. In case of dl, for $y < \bar{c}_{\mathsf{D}}^* \leq z$, the Y-user switches to Z, and the Z-user continues his technology. Both agents use the superior technology in $t = 2$. The same holds, mutatis mutandis, for $z < \bar{c}_{\mathsf{D}}^* \leq y$. However, for $(y, z) \in [0, \bar{c}_{\mathsf{D}}^*]^2$, both agents switch, while if $(y, z) \in [\bar{c}_{\mathsf{D}}^*, 1]^2$, both agents continue. In either case, the inferior technology is used at one site with probability one. Clearly, if $a_1^* = \bar{c}_{\mathsf{D}}^*$, then cl and dl would yield the same expected welfare. For given parameter values, they are, however, not the same. $\bar{c}_{\mathsf{D}}^*$ satisfies $\lambda \frac{\pi}{1+\pi} = E[Z] - \bar{c}_{\mathsf{D}}^*$ (see (7)), whereas a_1^* satisfies $\lambda \frac{\pi}{1+\pi} 4F(a_1^*)(1 - F(a_1^*)) = E[Z] - a_1^*$ (see (14)). As $4F(a_1)(1 - F(a_1)) < 1$ for all a_1, for given parameter values, the reputational gap in case of cl is smaller than in case of dl. As this gap equals the size of the distortion, $E[Z] - a_1^*$ or $E[Z] - \bar{c}_{\mathsf{D}}^*$, cl yields a higher expected welfare than dl.■

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