

Common learning and cooperation in repeated games

TAKUO SUGAYA

Graduate School of Business, Stanford University

YUICHI YAMAMOTO

Institute of Economic Research, Hitotsubashi University

We study repeated games in which players learn the unknown state of the world by observing a sequence of noisy *private* signals. We find that for generic signal distributions, the folk theorem obtains using ex post equilibria. In our equilibria, players *commonly* learn the state, that is, the state becomes asymptotic common knowledge.

KEYWORDS. Repeated game, private monitoring, incomplete information, ex post equilibrium, individual learning.

JEL CLASSIFICATION. C72, C73.

1. INTRODUCTION

In many economic activities, agents face uncertainty about the underlying payoff structure, and experimentation is useful to resolve such a problem. Suppose that two firms enter a new market. The firms are not familiar with the structure of the market and, in particular, do not know how profitable the market is (e.g., the intercept of the demand function). The firms interact repeatedly; every period, each firm chooses a price and then privately observes its sales level, which is stochastic due to an independent and identically distributed (i.i.d.) demand shock. Actions (prices) are perfectly observable. In this situation, the firms can eventually learn the true profitability of the market through sales; they may conclude that the market is profitable if they observe high sales frequently. However, since sales are private information, a firm faces uncertainty about whether the rival firm also believes that the market is profitable. Such *higher-order beliefs* have a significant impact on the firms' incentives. For example, suppose that choosing a high price is a "risky" action, in the sense that it yields a high profit only if the market is profitable enough *and* the rival firm also chooses a high price. Then even when a firm believes that the market is profitable, if it believes that the rival firm is pessimistic about the market profitability (and, hence, will choose a low price likely), it may prefer choosing a low price rather than a high price. Note also that each firm can manipulate the rival firm's belief (both the first- and higher-order beliefs) via a *signaling effect*: Even if firm A believes that the market is not very profitable, it may still be

Takuo Sugaya: tsugaya@stanford.edu

Yuichi Yamamoto: yyamamoto@ier.hit-u.ac.jp

The authors thank Michihiro Kandori, George Mailath, Stephen Morris, Andy Skrzypacz, and seminar participants at various places for helpful comments.

tempted to choose a high price today, because by doing so, firm B updates the posterior upward and starts to choose a high price in later periods, which is beneficial for firm A. Can the firms sustain collusion in such a situation? That is, is there an equilibrium in which they can coordinate on the high price if the market is profitable and on the low price if not? More generally, does a long-run relationship facilitate cooperation when players *privately* learn the unknown economic state?

To address this question, we develop a general model of *repeated games with individual learning*. In our model, Nature moves first and chooses the state of the world ω (e.g., the market profitability in the duopoly market). The state is fixed throughout the game and is not observable to players. Then players play an infinitely repeated game. Each period, players observe private signals, whose distribution depends on the state. A player's stage-game payoff depends both on actions and on her private signal, so the state (indirectly) influences expected payoffs through the signal distribution.

In general, when players have private information about the economic state, they can effectively coordinate their play if they *commonly learn* the state so that the state becomes almost common knowledge in the long run. [Cripps et al. \(2008\)](#) show that common learning indeed occurs if players learn the state from i.i.d. private signals. Unfortunately, their result does not apply to our setup, because (i) the signal distribution is influenced by actions, which are endogenously determined in equilibrium, and (ii) a player learns the state not only from her private signals, but from the opponents' actions. Accordingly, in our model, it is not obvious if common learning occurs. Another complication in our model is that while actions are perfectly observable, a player needs to rely on her private signals so as to detect the opponents' deviations, because, in general, the opponents choose different actions depending on their signals in equilibrium. In this sense, our model is a variant of repeated games with private monitoring, and it is well known that finding an equilibrium in such a model is a hard problem (see [Sugaya 2019](#), for example).

Despite such complications, we find that there indeed exist equilibria in which players commonly learn the state and obtain Pareto-efficient payoffs state by state. More generally, we find that the folk theorem holds so that any feasible and individually rational payoff (not only efficient outcomes) can be achievable as an equilibrium payoff. Our solution concept is an ex post equilibrium, in that our equilibrium strategy is a sequential equilibrium regardless of the state; so it is an equilibrium even if the initial prior changes.¹ For a fixed discount factor δ , the set of ex post equilibrium payoffs is smaller than the set of sequential equilibrium payoffs, because providing ex post incentives is more costly in general. However, it turns out that in our model, this cost becomes almost negligible as the discount factor approaches 1 and, accordingly, we can obtain the folk theorem using ex post equilibria.

¹ Some recent papers use ex post equilibria in different settings of repeated games, such as perfect monitoring and fixed states ([Hörner and Lovo 2009](#) and [Hörner et al. 2011](#)), public monitoring and fixed states ([Fudenberg and Yamamoto 2010, 2011](#)), private monitoring and fixed states ([Yamamoto 2014](#)), and changing states with an i.i.d. distribution ([Miller 2012](#)). Note also that there are many papers on ex post equilibria in undiscounted repeated games; see [Koren \(1992\)](#) and [Shalev \(1994\)](#), for example.

To establish the folk theorem, we need two conditions. The first condition is the *statewise full-rank* condition, which requires that there be an action profile such that different states generate different signal distributions, even if someone unilaterally deviates. This condition ensures that each player can learn the true state from private signals, and that no one can stop the opponents' state learning. The second condition is the *correlated learning* condition. Roughly, it requires that signals be correlated across players, so that a player's signal is informative about the opponents' signal. These conditions are not only sufficient, but "almost necessary" for our result. Indeed, if the statewise full-rank condition does not hold, one can obtain a payoff significantly higher than the minimax payoff by preventing the opponents' state learning. Also, if the correlated learning condition does not hold, we can construct an example in which the folk theorem cannot be obtained by ex post equilibria. See the working paper version (Sugaya and Yamamoto 2019) for more details.

Our proof of the folk theorem is constructive, and it builds on the idea of block strategies in Hörner and Olszewski (2006) and Wiseman (2012). For the sake of exposition, suppose for now that there are only two players and two states, ω_1 and ω_2 . In our equilibrium, the infinite horizon is divided into a sequence of *blocks*. At the beginning of the block, each player i chooses a *state-specific* plan about whether to reward or punish the opponent: Her plan is either reward the opponent at both states, punish the opponent at both states, reward at state ω_1 but punish at ω_2 , or reward at state ω_2 but punish at ω_1 . As explained shortly, the use of state-specific punishments is crucial so as to provide appropriate incentives in our environment.

In the first T periods of the block, player 1 collects private signals and makes an inference $\omega(1)$ about the state ω . Similarly, in the next T periods, player 2 makes an inference $\omega(2)$ about the state. We take T sufficiently large, so that each player i 's inference $\omega(i)$ matches the true state almost surely. Then in the next period, each player reports her inference $\omega(i)$ using actions, and checks whether they indeed agree on the state. Then depending on the reported information and on the plan chosen at the beginning of the block, the players adjust the continuation play in the rest of the block. For example, if both players report ω_1 and plan to reward each other at ω_1 , they will choose an action profile that yields high payoffs to both players at ω_1 . At the end of the block (again, via actions), players report their private signals during the learning phase in earlier periods; this information is used to make a minor modification to the continuation play (the punishment plan for the next block), which helps to provide the right incentives. Once the block is over, a new block starts and players behave as above again.

It is important that players make the inference $\omega(i)$ based only on the signals during the current block; it does not depend on the signals in the previous blocks. This property ensures that even if someone makes a wrong inference (i.e., $\omega(i)$ does not match the true state), it does not have a long-run impact on payoffs. Indeed, in the next block, players can learn the true state with high probability and adjust the continuation play. This implies that even if a player deviates during the learning phase, its impact on a long-run payoff is not very large, which helps to deter such a deviation.

We find that this “learning, communication, and coordination” mechanism works effectively and approximates the Pareto-efficient frontier. Also, common learning occurs in this equilibrium. A key is that players communicate truthfully in our equilibrium, which makes (a piece of) their private information public and facilitates common learning. So in our equilibrium, a signaling effect helps to achieve common learning.

A critical step in our proof is to show that it is indeed possible to provide appropriate incentives for such truthful communication.² To provide such truthful incentives, signal correlation plays a crucial role. Recall that player i makes an inference $\omega(i)$ using private signals pooled over the T -period interval. Since signals are correlated across players, the opponent's signal frequency f_{-i} during this interval is informative about player i 's signal frequency f_i and, hence, is informative about player i 's inference $\omega(i)$. This suggests that the opponent can statistically distinguish player i 's misreport. A similar idea appears in the mechanism design literature (e.g., [Cr  mer and McLean 1988](#)), but a new complication is that the unknown state ω influences the signal correlation, which makes signals ambiguous. For example, there may be player i 's signal that is highly correlated with the opponent's signal z_{-i} conditional on the state ω_1 , but is correlated with a different signal $\tilde{z}_{-i}$ conditional on the state ω_2 .

To deter player i 's misreport using such ambiguous signals, state-contingent punishments are helpful.³ A rough idea is that the opponent interprets her signal frequency f_{-i} *taking a state ω as given* and decides whether to punish player i for that state ω . For example, suppose that the opponent's signal frequency f_{-i} is typical of the state ω_1 , i.e., it is close to the true signal distribution at ω_1 . Then *conditional on the state ω_1* , the opponent believes that player i 's observation is also typical of the state ω_1 and, hence, i 's inference is $\omega(i) = \omega_1$. By contrast, *conditional on the state ω_2* , the opponent *may not* believe that player i 's inference is $\omega(i) = \omega_1$, since signals are interpreted differently at different states. Suppose now that player i reports $\omega(i) = \omega_1$. Should the opponent punish player i ? The point is that this report is consistent with the opponent's signals conditional on the state ω_1 , but not conditional on ω_2 . This suggests that the opponent should punish player i *only at the state ω_2* , by playing a continuation strategy that yields a low payoff to player i conditional on the state ω_2 but a high payoff conditional on ω_1 . That is, the opponent should choose the plan “reward player i at ω_1 but punish at ω_2 ” more likely in the next block.

In the proof, we carefully construct such a state-contingent punishment mechanism so that player i 's misreport is indeed deterred. In particular, we find that there is a punishment mechanism such that the following statements hold:

- (i) If everyone reports truthfully, the probability of a punishment being triggered is almost negligible.

²Allowing cheap-talk communication does not simplify our analysis due to the problem that we need to find a mechanism under which players report truthfully in the cheap-talk communication stage, and that is essentially the same as the problem we consider here.

³For this idea to work, it is crucial that players' signals are correlated *conditional on each state ω* . Indeed, if not and signals are independent at some state ω , they are uninformative about the opponent's observation conditional on that state and, hence, not useful to detect the opponent's misreport.

- (ii) The truthful report is ex post incentive compatible, that is, regardless of the true state ω and the true inference $\omega(i)$, reporting $\omega(i)$ truthfully is a best reply for each player i .

The first property ensures that even though a punishment destroys the total welfare (players choose inefficient actions once it is triggered), the equilibrium payoff can still approximate the Pareto-efficient outcome.⁴ The second property implies that any misreport is not profitable, regardless of player i 's belief about the state ω . This in particular implies that player i 's history in the previous blocks, which influences her belief about ω , is irrelevant to her incentive in the current block; her incentive is solely determined by her history within the current block. This allows us to use a recursive technique to construct an equilibrium in the infinite-horizon game.

The design of the state-contingent punishment mechanism is a bit complicated, because player i 's belief about the opponent's signal frequency f_{-i} is also influenced by the unknown state ω . For example, suppose that player i 's signal frequency f_i during the T -period interval is typical of the state ω_1 , so that her inference is $\omega(i) = \omega_1$. With such an observation f_i , *conditional on the state* ω_1 , she believes that the opponent believes that player i 's inference is $\omega(i) = \omega_1$ and, hence, the truthful report of $\omega(i) = \omega_1$ is a best reply. However, *conditional on the state* ω_2 , she *need not* believe that the opponent believes $\omega(i) = \omega_1$ in general. So to satisfy property (ii) above, we need to carefully design a (state-contingent) punishment mechanism for the state ω_2 , that is, reporting $\omega(i) = \omega_1$ must be a best reply for player i at ω_2 even though she does not expect the opponent to believe $\omega(i) = \omega_1$. More generally, we need to find a mechanism with which, for each given observation f_i , player i 's best reply does not depend on the state (the truthful report of $\omega(i)$ must be a best reply at *both* states), even though her belief about the opponent's belief depends on the state. One way to solve this problem is to let the opponent make player i indifferent over all reports, regardless of the observation f_{-i} ; then the truthful report of $\omega(i)$ is always a best reply for player i . But it turns out that such a mechanism does not satisfy the property (i) above and causes inefficiency, that is, a punishment is triggered with positive probability and destroys the total welfare even on the equilibrium path.⁵ To avoid such inefficiency while maintaining truthful incentives, we consider a mechanism in which the opponent makes player i indifferent only after *some* (but not all) observations f_{-i} . It turns out that this idea "almost" solves our problem, that is, it allows us to construct a mechanism in which the truthful report of the summary inference $\omega(i)$ is an *approximate* best reply regardless of the past history, while minimizing the welfare destruction. Of course, this is not an exact solution to our problem, as we need the truthful report to be an *exact* best reply. To fix this problem, in the last step of the proof, we modify the equilibrium strategy a bit: we let players reveal their signal sequence during the learning phase (this is different from $\omega(i)$, which is just

⁴Fudenberg et al. (1994) show that this inefficiency can be avoided if continuation payoffs take the form of "utility transfers." Unfortunately this technique does not seem to apply to our setup, because players condition their play on their private signals.

⁵This is similar to the fact that belief-free equilibria in Ely et al. (2005) cannot attain the Pareto-efficient outcome when monitoring is imperfect.

a summary statistics of the observed signals) at the end of each block, and use this information to provide an extra incentive to report the summary inference $\omega(i)$ truthfully. See Section 4.5 for more details.

Fudenberg and Yamamoto (2010) also use the idea of state-contingent punishments, but their proof is not constructive. In particular, both the state learning process and the intertemporal incentives are implicitly described through the motion of continuation payoffs. The interaction of these two forces complicates the motion of continuation payoffs, which makes it difficult to see how players learn the state in equilibrium and how they use this information to punish a deviator. In contrast, our proof is constructive, and we explicitly describe how each player learns the state in each block and chooses a state-contingent punishment plan. We hope that this helps people understand the role of state-contingent punishment in a more transparent way.

Throughout this paper, we assume that actions are perfectly observable. But this assumption is not crucial; in the working paper version (Sugaya and Yamamoto 2019), we extend the analysis to the case in which actions are not observable. In this new setup, players need to monitor the opponents' actions only through noisy private signals, whose distribution is influenced by the unknown state ω . So it is a repeated game with *private monitoring* and *unknown monitoring structure*. We find that the folk theorem still holds when the identifiability conditions are strengthened. This result generalizes various efficiency theorems for repeated games with private monitoring⁶ (in particular, the folk theorem of Sugaya (2019)) to the case in which the monitoring structure is unknown.

To the best of our knowledge, this is the first paper to consider common learning with strategic players.⁷ Cripps et al. (2008, 2013) consider the case in which players are not strategic, i.e., players observe private signals about the state each period without taking actions. They find that common learning occurs when signals are i.i.d., but it does not occur, in general, for non-i.i.d. signals. Our work extends their analysis by considering strategic players; now signal distributions are non-i.i.d., and *endogenously* determined by players' equilibrium play. It turns out that players' strategic behavior has a substantial impact on the joint learning outcome. We find that with strategic players, the negative result is overturned and common learning occurs in general, thanks to the signaling effect discussed above.

Our work belongs to the literature on learning in repeated games. Most of the existing work assumes that players observe *public* (or almost public) signals about the state,

⁶For example, the efficient outcome is approximately achieved in the prisoner's dilemma when observations are nearly perfect (Sekiguchi 1997, Bhaskar and Obara 2002, Piccione 2002, Ely and Välimäki 2002, Yamamoto 2007, 2009, Hörner and Olszewski 2006, Chen 2010, and Mailath and Olszewski 2011), nearly public (Mailath and Morris 2002, 2006 and Hörner and Olszewski 2009), statistically independent (Matsushima 2004, Yamamoto 2012), and even fully noisy and correlated (Kandori 2011, Fong et al. 2011, and Sugaya 2012, 2019). Kandori (2002) and Mailath and Samuelson (2006) provide excellent surveys. See also Lehrer (1990) for the case of no discounting and Fudenberg and Levine (1991) for the study of approximate equilibria with discounting.

⁷A recent paper by Basu et al. (2018) considers a similar question, but their analysis is quite different from ours because (i) they impose a special assumption on the payoff function (there are only two actions, and one of them is a dominant action) and (ii) they assume conditionally independent signals.

and focuses on equilibria in which players ignore private information (Wiseman 2005, 2012 and Fudenberg and Yamamoto 2010, 2011). An exception is Yamamoto (2014), who considers the case in which players learn from private signals only. The difference from this paper is that he focuses on *belief-free equilibria*, which are a subset of sequential equilibria. An advantage of belief-free equilibrium is its tractability; it does not require players' coordination, and a player's higher-order belief is payoff-irrelevant. But unfortunately, its payoff set is bounded away from the Pareto-efficient frontier, in general, due to the lack of coordination. To avoid such inefficiency, we consider sequential equilibria in which players coordinate their play through communication. As noted earlier, a player's best reply in such communication is very sensitive to her higher-order belief (her belief about the opponent's signals), which makes our analysis quite different from those in the literature.

2. REPEATED GAMES WITH INDIVIDUAL LEARNING

Given a finite set X , let ΔX be the set of probability distributions over X . Given a subset W of $\mathbb{R}^n$, let $\text{co } W$ denote the convex hull of W .

We consider an N -player infinitely repeated game in which the set of players is denoted by $I = \{1, \dots, N\}$. At the beginning of the game, Nature chooses the state of the world ω from a finite set Ω . Assume that players cannot observe the true state ω and let $\mu \in \Delta\Omega$ denote their common prior over ω .⁸ Throughout the paper, we assume that the game begins with symmetric information: Each player's initial belief about ω is equal to the prior μ . But it is straightforward to extend our analysis to the asymmetric-information case as in Fudenberg and Yamamoto (2011).⁹

Each period, players move simultaneously and each player $i \in I$ chooses an action a_i from a finite set A_i . The chosen action profile $a \in A \equiv \times_{i \in I} A_i$ is publicly observable and, in addition, each player i receives a private signal z_i about the state ω from a finite set Z_i . The distribution of the signal profile $z \in Z \equiv \times_{i \in I} Z_i$ depends on the state of the world ω and on the action profile $a \in A$, and is denoted by $\pi^\omega(\cdot|a) \in \Delta Z$. Let $\pi_i^\omega(\cdot|a)$ denote the marginal distribution of player i 's signal z_i given ω and a , that is, $\pi_i^\omega(z_i|a) = \sum_{z_{-i} \in Z_{-i}} \pi^\omega(z|a)$. Likewise, let $\pi_{-i}^\omega(\cdot|a)$ be the marginal distribution of the opponents' signals z_{-i} . Player i 's payoff is $u_i^\omega(a, z_i)$, so her expected payoff given the state ω and the action profile a is $g_i^\omega(a) = \sum_{z_i \in Z_i} \pi_i^\omega(z_i|a) u_i^\omega(a, z_i)$.¹⁰ Let $g^\omega(a) = (g_i^\omega(a))_{i \in I}$ be the payoff vector given ω and a . As usual, we write $\pi^\omega(\alpha)$ and $g_i^\omega(\alpha)$ for the signal distribution

⁸Because our arguments deal only with ex post incentives, they extend to games without a common prior. However, as Dekel et al. (2004) argue, the combination of equilibrium analysis and a noncommon prior is hard to justify.

⁹Specifically, all the results in this paper extend to the case in which each player i has initial private information θ_i about the true state ω , where the set Θ_i of player i 's possible private information is a partition of Ω . Given the true state $\omega \in \Omega$, player i observes $\theta_i^\omega \in \Theta_i$, where θ_i^ω denotes $\theta_i \in \Theta_i$ such that $\omega \in \theta_i$. In this setup, private information θ_i^ω allows player i to narrow down the set of possible states; for example, player i knows the state if $\Theta_i = \{(\omega_1), \dots, (\omega_o)\}$.

¹⁰If there are $\omega \in \Omega$ and $\tilde{\omega} \neq \omega$ such that $u_i^\omega(a, z_i) \neq u_i^{\tilde{\omega}}(a, z_i)$ for some $a_i \in A_i$ and $z \in Z$, then it might be natural to assume that player i does not observe the realized value of u_i as the game is played; otherwise players might learn the true state from observing their realized payoffs. Since we consider ex post equilibria, we do not need to impose such a restriction.

and the expected payoff when players play a mixed action profile $\alpha \in \times_{i \in I} \Delta A_i$. Similarly, we write $\pi^\omega(a_i, \alpha_{-i})$ and $g_i^\omega(a_i, \alpha_{-i})$ for the signal distribution and the expected payoff when players $-i$ play a mixed action $\alpha_{-i} \in \times_{j \neq i} \Delta A_j$.

As emphasized in the [Introduction](#), uncertainty about the payoff functions is common in applications. Examples that fit our model include the following.

- **Oligopoly market with unknown demand function.** Often times, firms do not have precise information about the market structure, and such a situation is a special example of our model. To see this, let I be the set of firms, let a_i be firm i 's price, and let z_i be firm i 's sales level. The distribution $\pi^\omega(\cdot|a)$ of sales levels depends on the unknown state ω , which means that the firms do not know the true distribution of the sales level.
- **Team production and private benefit.** Consider agents working on a joint project who do not know the profitability of the project; they may learn the true profitability through their experience over time. To describe such a situation, let I be the set of agents, let a_i be agent i 's effort level, and let z_i be agent i 's private profit from the project. The distribution $\pi^\omega(\cdot|a)$ of private profits depends on the unknown state ω , so the agents learn the true distribution through their observations over time.

In the infinitely repeated game, players have a common discount factor $\delta \in (0, 1)$. Let $(a^\tau, z_i^\tau) \in A \times Z_i$ be player i 's private observation in period τ and let $h_i^t = (a^\tau, z_i^\tau)_{\tau=1}^t$ be player i 's private history until period $t \geq 1$. Let $h_i^0 = \emptyset$ and for each $t \geq 0$, let H_i^t be the set of all private histories h_i^t . Let $h^t = (h_i^t)_{i \in I}$ denote a profile of t -period private histories and let H^t be the set of all history profiles h^t . A strategy for player i is defined to be a mapping $s_i : \bigcup_{t=0}^\infty H_i^t \rightarrow \Delta A_i$. Let S_i be the set of all strategies for player i and let $S = \times_{i \in I} S_i$.

The feasible payoff set for a given state ω is defined as

$$V(\omega) \equiv \text{co}\{g^\omega(a)|a \in A\},$$

that is, $V(\omega)$ is the convex hull of possible stage-game payoff vectors at the state ω . Then the feasible payoff set for the overall game is defined as

$$V \equiv \times_{\omega \in \Omega} V(\omega).$$

Thus each feasible payoff vector $v \in V$ specifies payoffs for each player and for each state, i.e., $v = ((v_1^\omega, \dots, v_N^\omega))_{\omega \in \Omega}$. Note that a given $v \in V$ may be generated using different action distributions at different states ω . We show that there are equilibria that approximate payoffs in V if the state is statistically identified by private signals so that players learn it over time.

Player i 's minimax payoff for a given state ω is defined as

$$m_i^\omega \equiv \min_{\alpha_{-i}} \max_{a_i} g_i^\omega(a_i, \alpha_{-i}).$$

Let $\underline{\omega}^\omega(i)$ denote the (possibly mixed) minimax action profile against player i conditional on ω . Let V^* be the set of feasible and individually rational payoffs, that is,

$$V^* \equiv \{v \in V \mid v_i^\omega \geq m_i^\omega \ \forall i \forall \omega\}.$$

Here the individual rationality is imposed state by state; i.e., V^* is the set of feasible payoffs such that each player obtains at least her minimax payoff for each state ω .¹¹ Throughout the paper, we assume that the set V^* is full dimensional.

CONDITION 1 (Full dimension). We have $\dim V^* = |I| \times |\Omega|$.

3. THE FOLK THEOREM WITH INDIVIDUAL LEARNING

In this section, we present our main result, the folk theorem for games with individual learning. In our equilibrium, common learning occurs, so that the state becomes approximate common knowledge even though players learn the state from private signals.

We use an ex post equilibrium as an equilibrium concept.

DEFINITION 1. A strategy profile s is an *ex post equilibrium* if it is a sequential equilibrium in the infinitely repeated game in which ω is common knowledge for each ω .

In an ex post equilibrium, after every history h^t , player i 's continuation play is a best reply regardless of the true state ω . Hence, these equilibria are robust to a perturbation of the initial prior, that is, an ex post equilibrium is a sequential equilibrium given any initial prior.

¹¹If there are only two players and our Condition 2 holds, the minimax payoff m_i^ω indeed characterizes player i 's minimum equilibrium payoff in the limit as $\delta \rightarrow 1$. Precisely, we can show that for any $v_i < \sum_{\omega \in \Omega} \mu(\omega) m_i^\omega$, there is $\bar{\delta} \in (0, 1)$ such that for any $\delta \in (\bar{\delta}, 1)$, player i 's expected payoff (here we consider the expected payoff given the initial prior μ) is at least v_i for all Nash equilibria. For simplicity, suppose that there are only two states, ω and $\bar{\omega}$. (It is not difficult to extend the argument to the case with more than two states.) Fix an arbitrary Nash equilibrium σ . Let a^* be as in Condition 2 and let σ_i^T be player i 's strategy with the following form:

- Play a^* for the first T periods and make an inference $\omega(i)$ as in Lemma 1.
- In each period $t > T$, choose $a_i \in \arg \max g_i^{\omega(i)}(\tilde{a}_i, \alpha_{-i} |_{\omega(i), h_i^{t-1}})$, where $\alpha_{-i} |_{\omega^*, h_i^{t-1}}$ is the distribution of the opponent's actions conditional on the history h_i^{t-1} and the true state ω^* .

From Lemma 1(i) and (ii), the probability that $\omega(i)$ coincides with the true state is at least $1 - 2 \exp(-T^{\frac{1}{2}})$, regardless of the opponent's play. Hence, if player i deviates to σ_i^T , her payoff is at least

$$(1 - \delta^T) \underline{g}_i + \delta^T \sum_{\omega^* \in \Omega} \mu(\omega^*) \{ (1 - 2 \exp(-T^{\frac{1}{2}})) m_i^{\omega^*} + 2 \exp(-T^{\frac{1}{2}}) \underline{g}_i \},$$

where $\underline{g}_i = \min_{\omega, a} g_i^\omega(a)$. Player i 's equilibrium payoff is at least this deviation payoff, which approximates $\sum_{\omega \in \Omega} \mu(\omega) m_i^\omega$ when we take $\delta \rightarrow 1$ and then $T \rightarrow \infty$. This proves the above claim. When there are more than two players, player i 's minimum equilibrium payoff can be below $\sum_{\omega \in \Omega} \mu(\omega) m_i^\omega$ even in the limit as $\delta \rightarrow 1$. This is because the opponents may be able to use correlated actions to punish player i when private signals are correlated.

We provide a set of conditions under which the folk theorem is established using ex post equilibria. Our first condition is the statewise full-rank condition of Yamamoto (2014), which requires that there be an action profile such that each player i can learn the true state ω from her private signal z_i .

CONDITION 2 (Statewise full rank). There is an action profile $a^* \in \mathcal{A}$ such that $\pi_i^\omega(\cdot|a_j, a_{-j}^*) \neq \pi_i^{\tilde{\omega}}(\cdot|a_j, a_{-j}^*)$ for each $i, j \neq i, a_j, \omega$, and $\tilde{\omega} \neq \omega$.

Intuitively, the statewise full rank implies that player i can statistically distinguish ω from $\tilde{\omega}$ through her private signal z_i , even if someone else unilaterally deviates from a^* .¹² We fix this profile a^* throughout the paper. Note that Condition 2 is satisfied for generic signal structures if $|Z_i| \geq 2$ for each i .

Our next condition is about the correlation of players' private signals. The following notation is useful. Let $\pi^\omega(z_{-i}|a, z_i)$ denote the conditional probability of z_{-i} given that the true state is ω , players play an action profile a , and player i observes z_i ; i.e.,

$$\pi^\omega(z_{-i}|a, z_i) = \frac{\pi^\omega(z|a)}{\pi_i^\omega(z_i|a)}.$$

Let $\pi^\omega(z_{-i}|a, z_i) = 0$ if $\pi_i^\omega(z_i|a) = 0$. Then let $C_i^\omega(a)$ be the matrix such that the rows are indexed by the elements of Z_{-i} , the columns are indexed by the elements of Z_i , and the (z_{-i}, z_i) component is $\pi^\omega(z_{-i}|a, z_i)$. Intuitively, the matrix $C_i^\omega(a)$ maps player i 's observations to her estimate (expectation) of the opponents' observations *conditional on the true state being ω* . To get the precise meaning, suppose that players played an action profile a for T periods and player i observed a signal sequence $(z_i^1, \dots, z_i^T)$. Let $f_i \in \Delta Z_i$ denote the corresponding signal frequency, i.e., let $f_i = (f_i[z_i])_{z_i \in Z_i}$, where $f_i[z_i] = \frac{|\{t \leq T | z_i^t = z_i\}|}{T}$ for each z_i . Given this observation f_i (and given the true state being ω), the conditional expectation of the opponents' signal frequency during these T periods is represented by $C_i^\omega(a)f_i$. So the matrix $C_i^\omega(a)$ converts player i 's signal frequency f_i to her estimate of the opponents' signal frequencies, when the state ω is given.

CONDITION 3 (Correlated learning). We have $C_i^\omega(a^*)\bar{\pi}_i^{\tilde{\omega}}(a^*) \neq \pi_{-i}^\omega(a^*)$ for each i and for each $(\omega, \tilde{\omega})$ with $\omega \neq \tilde{\omega}$.

Roughly, this condition requires that signals are correlated across players,¹³ so that if a player observes some "unusual" signal frequency, then she believes that the opponent's observation is also unusual. To better understand, suppose that players played a^*

¹² This condition is stronger than necessary. For example, our proof extends with no difficulty as long as for each $(i, \omega, \tilde{\omega})$ with $\omega \neq \tilde{\omega}$, there is an action profile a such that $\pi_i^\omega(\cdot|a'_j, a_{-j}) \neq \pi_i^{\tilde{\omega}}(\cdot|a'_j, a_{-j})$ for each $j \neq i$ and a'_j . That is, each player may use different action profiles to distinguish different pairs of states. But it significantly complicates the notation with no additional insights. Also, while Condition 2 requires that all players can learn the state from private signals, it is easy to see that our proof is valid as long as there are at least two players who can distinguish the state.

¹³ Condition 3 is only about signal correlation conditional on the action a^* ; we allow the signals to be independent across players if someone deviates from a^* . In the proof of the folk theorem, we construct an equilibrium in which such a deviation is not profitable. A key is that actions are observable, so players can detect such a deviation for sure and punish a deviator. See the proof of Lemma 3 for more details.

for a while and player i 's signal frequency was exactly the expected distribution $\pi_i^{\tilde{\omega}}(a^*)$ for some state $\tilde{\omega}$. Note that this signal frequency is unusual if the true state were $\omega \neq \tilde{\omega}$. **Condition 3** requires that in this case, player i believes that conditional on the state ω , the opponent's signal frequency is also unusual and different from the ex ante distribution $\pi_{-i}^{\omega}(a^*)$. This condition holds for generic signal structures, since it can be satisfied by (almost all) small perturbations of the matrix $C_i^{\omega}(a^*)$.¹⁴

The assumption above is weaker than that of [Wiseman \(2012\)](#), who proves the folk theorem for the case in which signals are almost public (i.e., highly correlated). He assumes that there is a cheap-talk game after each stage game and considers an equilibrium in which players report their private signals truthfully in this cheap-talk game. High correlation of signals is useful to provide incentives for the truthful report. The idea is that when signals are highly correlated, a player's signal today is very informative about the opponent's observation, so any misreport can be easily detected. In contrast, our assumption (**Condition 3**) needs only a minimal amount of correlation. In the proof, we consider an equilibrium in which players report their inference, which is a *summary statistic* of observations over T periods. When T is large enough and signals are correlated, the law of large numbers ensures that players have accurate information about the opponent's inference after *some* (but not all) histories. As we show, this property is enough to provide appropriate incentives.

We can prove that a folk theorem holds under **Conditions 1–3**. However, the proof for a general case is fairly complex, so in this paper, we focus on the special case in which (i) there are only two players and two states, and (ii) each player has sufficiently many actions. These extra assumptions significantly simplify the notation and the proof, and we believe that this is the best way to illustrate our key ideas; in the proof, we show that there are equilibria in which players learn the state from signals and communicate it via actions. See the working paper version ([Sugaya and Yamamoto 2019](#)) for how this idea extends to a general case.

The following proposition is the formal statement of our folk theorem. It asserts that there are ex post equilibria in which players eventually obtain payoffs as if they knew the true state and played an equilibrium for that state.

PROPOSITION 1. *Suppose that $|I| = |\Omega| = 2$ and $|A_i| \geq |Z_i|$.¹⁵ Suppose also that **Conditions 1–3** hold. Then the folk theorem holds, i.e., for any $v \in \text{int } V^*$, there is $\bar{\delta} \in (0, 1)$ such that for any $\delta \in (\bar{\delta}, 1)$, there is an ex post equilibrium with payoff v .*

Proposition 1 is about players' equilibrium payoffs, and it does not say anything about how players' beliefs about the state change over time. In the working paper version ([Sugaya and Yamamoto 2019](#)), we show that in any equilibrium constructed in the proof of **Proposition 1**, the state asymptotically becomes common knowledge among players. A rough idea is as follows.

¹⁴**Condition 3** does not hold if signals are conditionally independent, in that $\pi^{\omega}(z|a) = \prod_{i \in I} \pi_i^{\omega}(z_i|a)$ for all ω and a . In the working paper version ([Sugaya and Yamamoto 2019](#)), we present an example with conditionally independent signals in which ex post equilibria cannot approximate the Pareto-efficient frontier.

¹⁵This assumption greatly simplifies the structure of the “detailed report round” that appears in the proof.

In the proof of [Proposition 1](#), we consider an equilibrium in which players (i) learn the state from private signals, (ii) report these signals truthfully via actions, and then (iii) adjust the continuation play depending on the report. Thanks to the communication in phase (ii), all private signals in phase (i) become public information. (This is what we meant by the signaling effect in the [Introduction](#).) Also, in our equilibrium, signals observed in phases (ii) and (iii) do not influence the continuation play at all, that is, there is no correlation between these signals and the chosen actions. So the only way to learn the opponent's signals observed in phases (ii) and (iii) is to use correlation of private signals. As shown in [Cripps et al. \(2008\)](#), in such a situation, the state asymptotically becomes common knowledge. Hence, the result follows.

4. PROOF OF [PROPOSITION 1](#)

Fix an arbitrary payoff vector $v \in \text{int } V^*$. We construct an ex post equilibrium with payoff v by extending the idea of block strategies in [Hörner and Olszewski \(2006\)](#). A key difference from [Hörner and Olszewski \(2006\)](#) is that in our equilibrium, each player makes an inference about the state ω from private signals and publicly reports it so as to coordinate the continuation play. A crucial step in the proof is how to induce the truthful report of the inference.

For each state ω , we choose four values, $\underline{v}_1^\omega$, $\underline{v}_2^\omega$, $\bar{v}_1^\omega$, and $\bar{v}_2^\omega$, as in [Figure 1](#). That is, we choose these values so that the rectangle $\times_{i \in I} [\underline{v}_i^\omega, \bar{v}_i^\omega]$ is in the interior of the feasible and individually rational payoff set for ω , and contains the payoff v . Looking ahead, these values are “target payoffs” in our equilibrium: We construct an equilibrium in which player i 's payoff in the continuation game conditional on the state ω is $\underline{v}_i^\omega$ if the opponent plans to punish her and is $\bar{v}_i^\omega$ if the opponent plans to reward her.

For each state ω , we take four action profiles, $a^{\omega, GG}$, $a^{\omega, GB}$, $a^{\omega, BG}$, and $a^{\omega, BB}$, such that the corresponding stage-game payoffs surround the rectangle, as in [Figure 1](#). For-

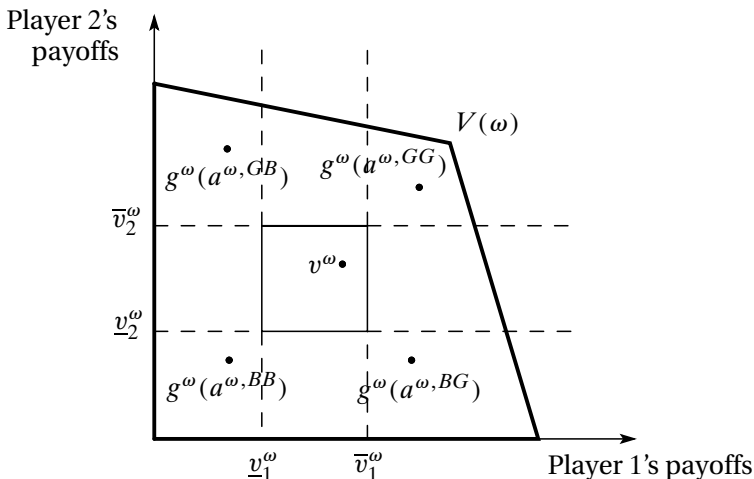


FIGURE 1. Actions $a^{\omega, GG}$, $a^{\omega, GB}$, $a^{\omega, BG}$, and $a^{\omega, BB}$.

mally, choose these profiles so that¹⁶

$$\max\{g_1^\omega(a^{\omega,BB}), g_1^\omega(a^{\omega,GB})\} < \underline{v}_1^\omega < \bar{v}_1^\omega < \min\{g_1^\omega(a^{\omega,GG}), g_1^\omega(a^{\omega,BG})\}$$

and

$$\max\{g_2^\omega(a^{\omega,BB}), g_2^\omega(a^{\omega,BG})\} < \underline{v}_2^\omega < \bar{v}_2^\omega < \min\{g_2^\omega(a^{\omega,GG}), g_2^\omega(a^{\omega,GB})\}.$$

Intuitively, the i th capital letter in the superscript (G for good, and B for bad) describes whether player i plans to reward or punish the opponent. Player i 's payoff is above $\bar{v}_i^\omega$ when the opponent rewards her and is below $\underline{v}_i^\omega$ when the opponent punishes her. Note that the definition of these action profiles is very similar to that in Hörner and Olszewski (2006).

Then we pick $\varepsilon > 0$ sufficiently small so that all the following conditions hold.

- For each ω ,

$$\max\{g_1^\omega(a^{\omega,GB}), g_1^\omega(a^{\omega,BB}), m_1^{\omega_1}\} < \underline{v}_1^\omega - \varepsilon \quad (1)$$

$$\max\{g_2^\omega(a^{\omega,BG}), g_2^\omega(a^{\omega,BB}), m_2^{\omega_2}\} < \underline{v}_2^\omega - \varepsilon \quad (2)$$

$$\min\{g_1^\omega(a^{\omega,GG}), g_1^\omega(a^{\omega,BG})\} > \bar{v}_1^\omega + 2\varepsilon \quad (3)$$

$$\min\{g_2^\omega(a^{\omega,GG}), g_2^\omega(a^{\omega,GB})\} > \bar{v}_2^\omega + 2\varepsilon. \quad (4)$$

- For each ω and $\tilde{\omega} \neq \omega$,

$$|\pi_{-i}^\omega(a^*) - C_i^\omega(a^*)\pi_i^{\tilde{\omega}}(a^*)| > 2\sqrt{\varepsilon}. \quad (5)$$

- For each ω , $\tilde{\omega} \neq \omega$, and $f_i \in \Delta Z_i$ with $|\pi_i^{\tilde{\omega}}(a^*) - f_i| < \varepsilon$,

$$|C_i^\omega(a^*)\pi_i^{\tilde{\omega}}(a^*) - C_i^\omega(a^*)f_i| < \sqrt{\varepsilon}. \quad (6)$$

Note that (5) indeed holds for small ε , thanks to Condition 3. Similarly, (1)–(4) follow from the definition of $a^{\omega,GG}$, $a^{\omega,GB}$, $a^{\omega,BG}$, and $a^{\omega,BB}$, and the fact that $\underline{v}_i^\omega$ is larger than the minimax payoff m_i^ω . Equation (5) follows from Condition 3. Equation (6) simply says that if an observation f_i is close to $\pi_i^{\tilde{\omega}}(a^*)$, then the posterior belief $C_i^\omega(a^*)f_i$ is close to $C_i^\omega(a^*)\pi_i^{\tilde{\omega}}(a^*)$. This inequality holds for any small ε , because $\frac{\sqrt{\varepsilon}}{\varepsilon} \rightarrow \infty$ as $\varepsilon \rightarrow 0$. In the rest of the proof, we fix this parameter ε .

4.1 Automaton with state-contingent punishment

In our equilibrium, the infinite horizon is divided into a series of *blocks* with length T_b , where a parameter T_b is to be specified. Each player i 's equilibrium strategy is described as an automaton strategy over blocks. At the beginning of the block, she chooses an automaton state x_i from the set $X_i = \{GG, GB, BG, BB\}$. (So there are four possible automaton states.) This automaton state x_i determines her play during the block; player i with an automaton state x_i plays a block strategy $s_i^{x_i}$ (to be specified). See Figure 2.

¹⁶For some payoff function, such action profiles a^{ω,x^ω} may not exist. In this case, as in Hörner and Olszewski (2006), we take action sequences $(a^{\omega,x^\omega}(1), \dots, a^{\omega,x^\omega}(n))$ instead of action profiles; the rest of the proof extends to this case with no difficulty.

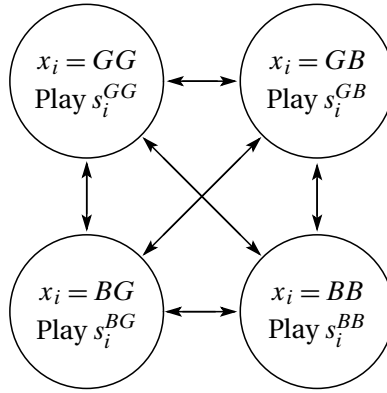


FIGURE 2. Automaton.

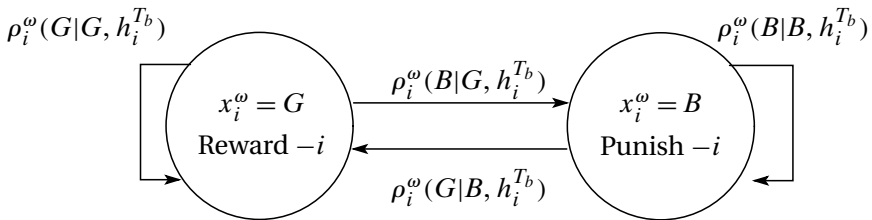


FIGURE 3. Transition of x_i^ω .

The automaton state x_i can be interpreted as player i 's *state-contingent plan* about whether to reward or punish the opponent. To be more precise, note that each automaton state x_i consists of two components, and let $x_i^{\omega_1} \in \{G, B\}$ denote the first component and let $x_i^{\omega_2} \in \{G, B\}$ denote the second. The first component $x_i^{\omega_1}$ represents player i 's plan about whether to punish the opponent *if the true state were* ω_1 . Similarly, the second component $x_i^{\omega_2}$ represents her plan *if the true state were* ω_2 . For example, if player i 's automaton state is $x_i = GB$, then during the current block, she rewards the opponent at state ω_1 and punishes the opponent at state ω_2 . (In other words, we choose the corresponding block strategy s_i^{GB} so that it yields a high payoff to the opponent conditional on ω_1 , but a low payoff conditional on ω_2 .) Likewise, if $x_i = BG$, she punishes the opponent at state ω_1 , but rewards at state ω_2 . If $x_i = GG$, she rewards the opponent at both states. If $x_i = BB$, she punishes the opponent at both states.

After the block, each player i chooses a new automaton state (plan) $\tilde{x}_i = (\tilde{x}_i^{\omega_1} \tilde{x}_i^{\omega_2})$ for the next block. Specifically, for each state ω , the new plan for the state ω is determined by a *transition rule* $\rho_i^\omega(\cdot | x_i^\omega, h_i^{T_b}) \in \Delta\{G, B\}$; that is, given the current plan x_i^ω and the current block history $h_i^{T_b}$, player i randomly selects a new plan $\tilde{x}_i^\omega \in \{G, B\}$ according to this distribution ρ_i^ω . Note that the current plan $x_i^{\tilde{\omega}}$ for state $\tilde{\omega}$ does not directly influence the new plan $\tilde{x}_i^\omega$ for state $\omega \neq \tilde{\omega}$. See Figure 3

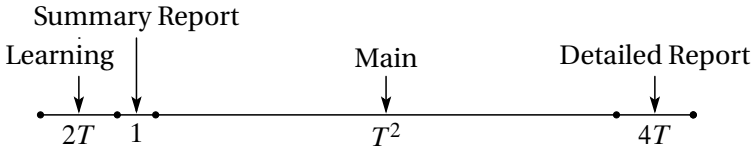


FIGURE 4. Structure of the block. Time goes from left to right.

In what follows, we carefully choose the block strategies s_i^{GG} , s_i^{GB} , s_i^{BG} , and s_i^{BB} and the transition rules $\rho_i^{\omega_1}$ and $\rho_i^{\omega_2}$ so that the resulting automaton strategy is indeed an equilibrium.

4.2 Block strategy $s_i^{x_i}$

4.2.1 Brief description Let $T_b = 2T + 1 + T^2 + 4T$, where $T > 0$ is to be specified. As noted, we regard the infinite horizon as a sequence of blocks with length T_b . Each block is further divided into four parts: The first $2T$ periods of the block are the *learning round*, the next period is the *summary report round*, and then the next T^2 periods are the *main round*. The remaining $4T$ periods are the *detailed report round*. See Figure 4.

As will be explained, we choose T sufficiently large so that the main round is much longer than the other rounds. Thus, the average payoff during the block is approximately the payoff during the main round. In other words, the payoffs during the learning round and the two report rounds are almost negligible.

The role of each round is roughly as follows.

Learning round The first T periods of the learning round are player 1's learning round, in which player 1 collects private signals and makes an inference $\omega(1)$ about the true state ω . The next T periods are player 2's learning round, in which player 2 makes an inference $\omega(2)$ about the state. During the learning round, players play the action profile a^* , so Condition 2 ensures that players can indeed distinguish the state statistically. Player i 's inference $\omega(i)$ takes one of three values: ω_1 , ω_2 , or $\emptyset$. Roughly, she chooses $\omega(i) = \omega_1$ if the signal frequency during her learning round is close to the true distribution $\pi_i^{\omega_1}(a^*)$ at ω_1 and she chooses $\omega(i) = \omega_2$ if it is close to the true distribution $\pi_i^{\omega_2}(a^*)$ at ω_2 . Otherwise, she chooses a “null” inference $\omega(i) = \emptyset$. More details are given in the next subsection. Let $T(i)$ denote the set of the periods included in player i 's learning round; that is, $T(1) = \{1, \dots, T\}$ and $T(2) = \{T + 1, \dots, 2T\}$.

Summary report round The next period is the summary report round, in which each player i publicly reports her inference $\omega(i)$ using her action. For simplicity, we assume that each player has at least three actions, so that she can indeed represent $\omega(i) \in \{\omega_1, \omega_2, \emptyset\}$ by one-shot actions.¹⁷ This “communication” allows players to coordinate their continuation play. Note that $\omega(i)$ is just a summary statistic of player i 's

¹⁷This assumption is not essential. If there is a player who has only two actions, we can modify the structure of the block so that the summary report round consists of two periods and each player represents her inference by a sequence of actions. The rest of the proof remains the same. (When the summary report round consists of two periods, each player can obtain partial information about the opponent's inference $\omega(-i)$ after the first period of the summary report round. But this information does not influence players'

observation during the learning round and, hence, this round is called the *summary report*.

Main round The next T^2 periods comprise the main round, in which players coordinate their play depending on the information revealed in the summary report round. If players report the same state ω in the summary report round, then players play the block strategy of Hörner and Olszewski (2006) during the main round.

- If both players report the same state ω in the summary report round, then in the first period of the main round, they “communicate” again and each player i reports her current plan $x_i^\omega \in \{G, B\}$ for this state ω . After that, players choose the action profile a^{ω, x^ω} until the main round ends, where $x^\omega = (x_1^\omega, x_2^\omega)$ is the reported plan. (Recall that this action profile a^{ω, x^ω} is chosen as in Figure 1.) If someone (say player i) deviates from this action profile a^{ω, x^ω} , she will be minimaxed by $\underline{\alpha}^\omega(i)$; that is, players minimax the deviation, assuming that the summary report ω is the true state.

So if players report the same state ω in the summary report round, they coordinate their play during the main round and choose an action profile that is consistent with the current plan. By the definition of the action a^{ω, x^ω} , each player i obtains a payoff higher than $\bar{v}_i^\omega$ if the opponent plans to reward her (i.e., $x_{-i}^\omega = G$) and a payoff lower than $\underline{v}_i^\omega$ if the opponent plans to punish her (i.e., $x_{-i}^\omega = B$).

If players’ reports in the summary report round do not coincide or if someone reports the null inference $\omega(i) = \emptyset$, they adjust their play in the following way.

- If one player reports ω but the other reports $\emptyset$, then the play during the main round is the same as above. (Intuitively, reporting $\omega(i) = \emptyset$ is treated as an abstention.)
- If both players report $\emptyset$, then the play during the main round is the same as the case in which both players report ω_1 .
- If one player reports ω_1 while the other reports ω_2 , then each player i reveals $x_i^{\omega(i)}$ in the first period of the main round and then chooses the minimax action $\underline{\alpha}_i^{\omega(i)}(-i)$, where $\omega(i)$ denotes the state reported by player i . That is, each player minimaxes the opponent, assuming that her own summary report is the true state.

Detailed report round The remaining $4T$ periods of the block comprise the detailed report round. Recall that in the summary report round, each player reports only $\omega(i)$, which is a *summary statistic* of her observation during the learning round. Now, in the detailed report round, each player reports her *full history* during the learning round. Specifically, in the first T periods, player 1 reports her observation $(z_1^t)_{t \in T(1)}$ during her own learning round. The assumption $|A_i| \geq |Z_i|$ ensures that players can reveal her signal z_i by choosing one action, so she can indeed report her signal sequence $(z_1^t)_{t \in T(1)}$

incentives, that is, the truthful report of $\omega(i)$ is still a best reply. This is so because in our equilibrium, the truthful report of $\omega(i)$ is a best reply regardless of the opponent’s inference $\omega(-i)$.)

using T periods. In the next T periods, player 2 reports her observation $(z_2^t)_{t \in T(2)}$ during her own learning round. After that, player 1 reports her observation $(z_1^t)_{t \in T(2)}$ during the opponent's learning round and then player 2 reports $(z_2^t)_{t \in T(1)}$. This information (the detailed report) can be used to double-check whether the opponent's summary report earlier was truthful and it influences the choice of the new automaton state $\hat{x}_i$ for the next block. We explain more on this later.

For each automaton state x_i , let $s_i^{x_i}$ be the block strategy that chooses actions as described above. That is, $s_i^{x_i}$ chooses the action a_i^* and makes the inference $\omega(i)$ in the learning round, reports the summary inference $\omega(i)$ in the summary report round, coordinates the play as above in the main round, and then reports the actual signal sequence $(z_i^t)_{t \in T(i)}$ in the detailed report round. The definition of $s_i^{x_i}$ here is informal, because we have not explained how player i forms $\omega(i)$.

REMARK 1. Why do we want to have a learning round for each player i separately? A point is that with this structure, player i 's inference $\omega(i)$ (the first-order belief in some sense) and her belief about the opponent's inference $\omega(-i)$ (the second-order belief in some sense) are made from different information sources: Player i 's first-order belief depends only on her history during her own learning round, while her second-order belief depends only on her history during the *opponent's* learning round. This means that even if player i reports $\omega(i)$ in the summary report round, it does not reveal her second-order belief to the opponent. This property is crucial to providing appropriate incentives for the detailed report round. See the proof of [Lemma 3](#) for more details.

4.2.2 Inference rule To complete the definition of the block strategy $s_i^{x_i}$, we explain how each player i forms the inference $\omega(i)$ during her learning round.

Recall that player i 's learning round consists of T periods. Let h_i^T denote player i 's history during this round and let H_i^T denote the set of all such histories. Player i 's *inference rule* is defined as a mapping $P: H_i^T \rightarrow \Delta\{\omega_1, \omega_2, \emptyset\}$. That is, given a private history h_i^T , player i (randomly) chooses the inference $\omega(i)$ from the set $\{\omega_1, \omega_2, \emptyset\}$ according to the distribution $P(\cdot|h_i^T)$. It is important that we allow player i to choose $\omega(i)$ randomly; this property is needed to prove [Lemma 1](#) below.

Given an inference rule P , let $\hat{P}(\cdot|\omega, a^1, \dots, a^T)$ denote the conditional distribution of $\omega(i)$ induced by P given that the true state is ω and players play the action sequence $(a^1, \dots, a^T)$ during player i 's learning round. That is,

$$\hat{P}(\cdot|\omega, a^1, \dots, a^T) = \sum_{h_i^T \in H_i^T} \Pr(h_i^T|\omega, a^1, \dots, a^T) P(\cdot|h_i^T),$$

where $\Pr(h_i^T|\omega, a^1, \dots, a^T)$ denotes the probability of h_i^T when the true state is ω and players play $(a^1, \dots, a^T)$. Likewise, for each $t \in \{0, \dots, T-1\}$ and h^t , let $\hat{P}(\cdot|\omega, h_{-i}^t, a^{t+1}, \dots, a^T)$ be the conditional distribution of $\omega(i)$ given that the true state is ω , the opponent's history up to the t th period is $h_{-i}^t = (a^t, z_{-i}^t)_{\tau=1}^t$, and players play $(a^{t+1}, \dots, a^T)$ thereafter. Given h_i^T , let $f_i(h_i^T) \in \Delta Z_i$ denote player i 's signal frequency induced by h_i^T . That is, $f_i(h_i^T)[z_i] = \frac{|\{t|z_i^t=z_i\}|}{T}$ for each z_i .

The following lemma shows that there is an inference rule P that satisfies some useful properties. The proof is similar to Fong et al. (2011) and Sugaya (2019), and can be found in the Appendix. Recall that ε is fixed so that (1)–(6) hold.

LEMMA 1. Suppose that Condition 2 holds. Then there is $\bar{T}$ such that for any $T > \bar{T}$, there is an inference rule $P : H_i^T \rightarrow \Delta\{\omega_1, \omega_2, \emptyset\}$ that satisfies the following properties.

(i) If players do not deviate from a^* , the inference $\omega(i)$ coincides with the true state with high probability: For each ω ,

$$\hat{P}(\omega(i) = \omega | \omega, a^*, \dots, a^*) \geq 1 - \exp(-T^{\frac{1}{2}}).$$

(ii) Regardless of the past history, the opponent's deviation cannot manipulate player i 's inference with high probability: For each ω , $t \in \{0, \dots, T-1\}$, h^t , $(a^\tau)_{\tau=t+1}^T$, and $(\tilde{a}^\tau)_{\tau=t+1}^T$ such that $a_i^\tau = \tilde{a}_i^\tau = a_i^*$ for all $\tau \geq t+1$,

$$|\hat{P}(\cdot | \omega, h_{-i}^t, a^{t+1}, \dots, a^T) - \hat{P}(\cdot | \omega, h_{-i}^t, \tilde{a}^{t+1}, \dots, \tilde{a}^T)| \leq \exp(-T^{\frac{1}{2}}).$$

(iii) Suppose that no one deviates from a^* . Then player i 's inference is $\omega(i) = \omega$ only if her signal frequency is close to the true distribution $\pi_i^\omega(a^*)$ at ω : For all $h_i^T = (a^t, z_i^t)_{t=1}^T$ such that $a^t = a^*$ for all t and such that $P(\omega(i) = \omega | h_i^T) > 0$,

$$|\pi_i^\omega(a^*) - f_i(h_i^T)| < \varepsilon.$$

Statement (i) ensures that state learning is almost perfect. Statement (ii) asserts that state learning is robust to the opponent's deviation *after every history*. To see its precise meaning, suppose that the first t periods of player i 's learning round are over and the opponent's history during these periods was h_{-i}^t . The opponent can deviate in the remaining periods, but statement (ii) implies that it cannot influence player i 's inference much. Note that both statements (i) and (ii) are natural consequences of Condition 2, which guarantees that player i can learn the true state even if someone else unilaterally deviates. Statement (iii) implies that player i makes the inference $\omega(i) = \omega$ only when her signal frequency is close to the true distribution $\pi_i^\omega(a^*)$ at state ω . So if player i 's signal frequency is not close to $\pi_i^{\omega_1}(a^*)$ or $\pi_i^{\omega_2}(a^*)$, her inference must be $\omega(i) = \emptyset$. (By contrast, as can be seen from the proof of the lemma, player i mixes $\omega(i) = \omega$ and $\omega(i) = \emptyset$ if her signal frequency is close to $\pi_i^\omega(a^*)$; see Figure 5.)

Statement (iii) is useful when we derive a bound on player i 's higher-order belief (i.e., player i 's belief about the opponent's signal frequency f_{-i} , which is informative about player i 's inference $\omega(i)$ about the state). Let $\Pr(f_{-i} | \omega, a^*, \dots, a^*, f_i)$ denote the probability of the opponent's signal frequency being f_{-i} , given that the true state is ω , players play a^* for T periods, and player i 's signal frequency during these periods is f_i . Then we have the following lemma.

LEMMA 2. Suppose that Condition 3 holds. Then there is $\bar{T}$ such that for any $T > \bar{T}$, ω , $\tilde{\omega} \neq \omega$, and h_i^T such that $|f_i(h_i^T) - \pi_i^{\tilde{\omega}}(a^*)| < \varepsilon$, we have

$$\sum_{f_{-i} : |f_{-i} - \pi_{-i}^\omega(a^*)| < \varepsilon} \Pr(f_{-i} | \omega, a^*, \dots, a^*, f_i(h_i^T)) < \exp(-T^{\frac{1}{2}}).$$

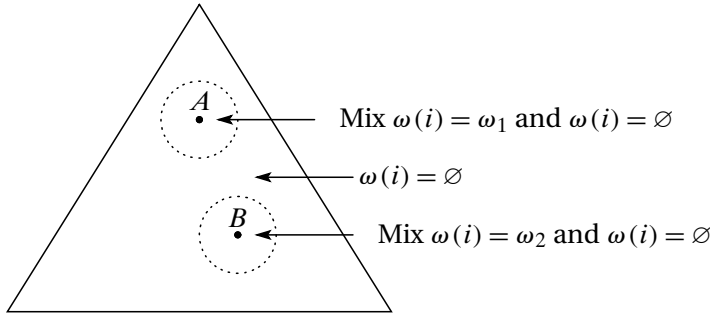


FIGURE 5. The triangle is the set of signal frequencies ΔZ_i . The point A denotes $\pi_i^{\omega_1}(a^G)$, while B denotes $\pi_i^{\omega_2}(a^G)$.

Roughly, this lemma implies that if player i has the inference $\omega(i) = \tilde{\omega}$ (which is unusual conditional on the state $\omega \neq \tilde{\omega}$), then she believes that conditional on the state ω , the opponent's observation is also unusual and not close to the ex ante distribution $\pi_{-i}^{\omega}(a^*)$. To see this, suppose that player i 's inference is $\omega(i) = \tilde{\omega}$. Then from Lemma 1(iii), we must have $|f_i(h_i^T) - \pi_i^{\tilde{\omega}}(a^*)| < \varepsilon$. Then from the lemma above, player i believes that the opponent's observation is not close to the ex ante distribution. As will be explained, this result plays a crucial role in inducing the truthful summary report.

PROOF OF LEMMA 2. Pick h_i^T such that

$$|\pi_i^{\tilde{\omega}}(a^*) - f_i(h_i^T)| < \varepsilon.$$

Using (6), we have

$$|C_i^{\omega}(a^*)\pi_i^{\tilde{\omega}}(a^*) - C_i^{\omega}(a^*)f_i(h_i^T)| \leq \sqrt{\varepsilon}.$$

Combining this with (5) yields

$$|C_i^{\omega}(a^*)f_i(h_i^T) - \pi_{-i}^{\omega}(a^*)| \geq \sqrt{\varepsilon}.$$

Accordingly, so as to have $|\pi_{-i}^{\omega}(a^*) - f_{-i}| < \varepsilon$, the distance between $C_i^{\omega}(a^*)f_i(h_i^T)$ and f_{-i} must be at least $\sqrt{\varepsilon} - \varepsilon$. However, Hoeffding's inequality implies that the probability of such an event is less than $\exp(-T^{\frac{1}{2}})$ for sufficiently large T . $\square$

REMARK 2. Allowing the null inference $\omega(i) = \emptyset$ is important. As noted in the Introduction, given player i 's observation f_i , different states induce different beliefs about the opponent's observation f_{-i} . In particular, at the point $f_i = C$ in Figure 6, player i has “conflicting beliefs” at different states; she believes that (i) conditional on the state ω_1 , the opponent's signal frequency f_{-i} is typical of the state ω_1 so that the opponent believes that player i 's inference is $\omega(i) = \omega_1$, but (ii) conditional on the state ω_2 , the opponent's signal frequency f_{-i} is typical of the state ω_2 so that the opponent believes that player i 's inference is $\omega(i) = \omega_2$. In this case, reporting $\omega(i) = \omega_1$ cannot be a best reply at the state ω_2 , because it contradicts the opponent's expectation illustrated in

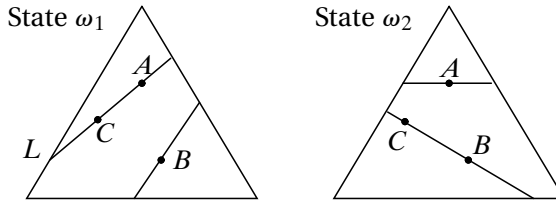


FIGURE 6. Each line in the left triangle is the set of signal frequencies f_i that give the same expectation about the opponent's signal frequency at the state ω_1 . That is, $C_i^{\omega_1}(a^*)f_i = C_i^{\omega_1}(a^*)\tilde{f}_i$ for any f_i and $\tilde{f}_i$ on the same line. At the point $f_i = A$, player i believes that the opponent's observation is typical of the state ω_1 in that $C_i^{\omega_1}(a^*)f_i = \pi_{-i}^{\omega_1}(a^*)$, so the same is true at the point $f_i = C$. Likewise, each line in the right triangle is the set of f_i that induce the same expectation at the state ω_2 . At the point $f_i = B$, player i believes that the opponent's observation is typical of the state ω_2 and the same is true at the point $f_i = C$.

(ii) above and triggers a state-contingent punishment. (See the proof of Lemma 3 for the formal description of the punishment mechanism.) At the same time, reporting $\omega(i) = \omega_2$ cannot be a best reply at the state ω_1 , as it contradicts the opponent's expectation described in (i). So reporting $\omega(i) = \omega_1$ and $\omega(i) = \omega_2$ cannot be ex post incentive compatible when player i has such conflicting beliefs. Instead, in our equilibrium, she makes the null inference $\omega(i) = \emptyset$ and reports it truthfully when she has such conflicting beliefs.

4.3 Transition rule ρ_i and equilibrium conditions

We have defined the block strategy $s_i^{x_i}$: Players learn the state in the learning round, report the summary inference $\omega(i)$ in the summary report round, coordinate the play in the main round, and then report the full information in the detailed report round. What remains is to find transition rules $\rho_i^{\omega_1}$ and $\rho_i^{\omega_2}$ so that the resulting automaton strategy is an equilibrium.

Formally, we choose the transition rules so that both the *promise-keeping condition* and the *incentive-compatibility condition* hold. The promise-keeping condition requires that the target payoffs be exactly achieved *state by state*; for example, if the opponent's current automaton state is $x_{-i} = GB$, player i 's payoff in the continuation game must be $\bar{v}_i^{\omega_1}$ conditional on the state ω_1 (since player i is rewarded at ω_1) and be $\underline{v}_i^{\omega_2}$ conditional on the state ω_2 (since player i is punished at ω_2). Formally, it requires

$$\begin{aligned} \bar{v}_i^{\omega} = & (1 - \delta^{T_b}) \sum_{t=1}^{T_b} \delta^{t-1} E[g_i^{\omega}(a^t) | \omega, s^x] \\ & + \delta^{T_b} \{ \bar{v}_i^{\omega} - E[\rho_{-i}^{\omega}(B|G, h_{-i}^{T_b}) | \omega, s^x] (\bar{v}_i^{\omega} - \underline{v}_i^{\omega}) \} \end{aligned} \quad (7)$$

for each ω , i , and $x = (x_1, x_2)$ with $x_{-i}^\omega = G$, and

$$\begin{aligned} \underline{v}_i^\omega &= (1 - \delta^{T_b}) \sum_{t=1}^{T_b} \delta^{t-1} E[g_i^\omega(a^t) | \omega, s^x] \\ &\quad + \delta^{T_b} \{ \underline{v}_i^\omega + E[\rho_{-i}^\omega(G|B, h_{-i}^{T_b}) | \omega, s^x] (\bar{v}_i^\omega - \underline{v}_i^\omega) \} \end{aligned} \quad (8)$$

for each ω , i , and x with $x_{-i}^\omega = B$. Equation (7) asserts that if $x_{-i}^\omega = G$ so that the opponent plans to reward player i for the state ω , then player i 's payoff in the continuation game is exactly $\bar{v}_i^\omega$ conditional on the state ω . Indeed, the first term on the right-hand side is player i 's payoff in the current block and the second term is her continuation payoff. (The term $E[\rho_{-i}^\omega(B|G, h_{-i}^{T_b}) | \omega, s^x]$ is the probability that the opponent switches to the punishment plan $x_{-i}^\omega = B$ after the block, in which case player i 's continuation payoff goes down from $\bar{v}_i^\omega$ to $\underline{v}_i^\omega$.) Similarly, (8) asserts that if the opponent plans to punish player i for the state ω , player i 's payoff in the continuation game is $\underline{v}_i^\omega$ conditional on the state ω . The above conditions imply that player i 's payoff is solely determined by the opponent's plan x_{-i} and is independent of her own plan x_i . (While her current block payoff depends on the plan x_i , this effect is offset by the continuation payoffs, so the total payoff is indeed independent of x_i .) So in each block, player i is indifferent over the four strategies s_i^{GG} , s_i^{GB} , s_i^{BG} , and s_i^{BB} . This in turn implies that randomizing the automaton state x_i at the beginning of the block is indeed a best reply for player i .

The incentive-compatibility condition requires that deviating to any other block strategy $s_i^{T_b} \neq s_i^{x_i}$ be not profitable, in each period of the block. That is,

$$\begin{aligned} &(1 - \delta^{T_b-t}) \sum_{\tau=t+1}^{T_b} \delta^{\tau-1} (E[g_i^\omega(a^\tau) | \omega, s_i^{T_b}, s_{-i}^{x_{-i}}, h_i^t] - E[g_i^\omega(a^\tau) | \omega, s^x, h_i^t]) \\ &\leq \delta^{T_b-t} (E[\rho_{-i}^\omega(B|G, h_{-i}^{T_b}) | \omega, s_i^{T_b}, s_{-i}^{x_{-i}}, h_i^t] \\ &\quad - E[\rho_{-i}^\omega(B|G, h_{-i}^{T_b}) | \omega, s^x, h_i^t]) (\bar{v}_i^\omega - \underline{v}_i^\omega) \end{aligned} \quad (9)$$

for each ω , i , $s_i^{T_b}$, t , h_i^t , and x with $x_{-i}^\omega = G$, and

$$\begin{aligned} &(1 - \delta^{T_b-t}) \sum_{\tau=t+1}^{T_b} \delta^{\tau-1} (E[g_i^\omega(a^\tau) | \omega, s_i^{T_b}, s_{-i}^{x_{-i}}, h_i^t] - E[g_i^\omega(a^\tau) | \omega, s^x, h_i^t]) \\ &\leq \delta^{T_b-t} (E[\rho_{-i}^\omega(B|B, h_{-i}^{T_b}) | \omega, s_i^{T_b}, s_{-i}^{x_{-i}}, h_i^t] \\ &\quad - E[\rho_{-i}^\omega(B|B, h_{-i}^{T_b}) | \omega, s^x, h_i^t]) (\bar{v}_i^\omega - \underline{v}_i^\omega) \end{aligned} \quad (10)$$

for each ω , i , $s_i^{T_b}$, t , h_i^t , and x with $x_{-i}^\omega = B$. Here the left-hand side measures how much the block payoff increases by deviating in period $t + 1$ of the block and the right-hand side measures how much it decreases the continuation payoff after the block. So these inequalities imply that in any period of the block, deviating from the prescribed strategy

$s_i^{x_i}$ is not profitable, regardless of the true state. Accordingly, the resulting automaton strategy is an ex post equilibrium.

4.4 Complete-information transfer game

In what follows, we explain how to find the transition rules that satisfy the above conditions (7)–(10). This completes our proof, because the resulting automaton strategy is indeed an equilibrium and any payoff in the set $\times_{\omega \in \Omega} \times_{i \in I} [\underline{v}_i^\omega, \bar{v}_i^\omega]$ can be achieved by randomizing the initial automaton state. In particular, the payoff v is exactly achievable.

It turns out that finding such transition rules is equivalent to finding appropriate “transfer rules.” This is so because continuation payoffs after the block play a role like that of transfers in the mechanism design. A similar idea appears in various past work, e.g., [Fudenberg and Levine \(1994\)](#).

As such, we focus on the following *complete-information transfer game*. Consider a repeated game with T_b periods. Assume complete information, so that a state ω is given and is common knowledge. After the game, player i receives a transfer according to some transfer rule $U_i^\omega : H_{-i}^{T_b} \rightarrow \mathbf{R}$, so player i ’s (unnormalized) payoff in this game is

$$\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) + \delta^{T_b} U_i^\omega(h_{-i}^{T_b}).$$

Let $G_i^\omega(s^{T_b}, U_i^\omega)$ denote player i ’s expected payoff in this game when players play s^{T_b} . Also, for each history h_i^t with $t \leq T_b$, let $G_i^\omega(s^{T_b}, U_i^\omega, h_i^t)$ denote player i ’s payoff in the continuation game after history h_i^t .

A few remarks are in order. First, this is the complete-information game, so the state ω is given and is common knowledge. The analysis of this complete-information game is useful, because our goal is to construct an equilibrium that satisfies the ex post incentive-compatibility conditions (9) and (10); these conditions require that player i ’s deviation be not profitable even when the state ω is publicly revealed at the beginning of the game.

Second, the transfer U_i^ω is state-specific, that is, we use different transfer rules U_i^ω for different states ω . This captures the idea that punishments are state-specific in our equilibrium in the infinite-horizon game. Specifically, once the block is over, the opponent chooses a state-specific punishment plan $x_{-i} = (x_{-i}^{\omega_1}, x_{-i}^{\omega_2})$ for the continuation game and player i ’s continuation payoff conditional on ω is solely determined by the punishment plan x_{-i}^ω for the state ω (see (7) and (8)). Since the opponent chooses these plans $x_{-i}^{\omega_1}$ and $x_{-i}^{\omega_2}$ independently, player i ’s continuation payoffs for different states take quite different values. Hence, the transfer rule U_i^ω should depend on ω .

Third, the amount of the transfer depends on the opponent’s history $h_{-i}^{T_b}$, but not on player i ’s history $h_i^{T_b}$. Again this comes from the fact that player i ’s continuation payoff is determined by the opponent’s plan x_{-i} , which is influenced by the opponent’s history $h_{-i}^{T_b}$ but not by $h_i^{T_b}$.

Our goal in this subsection is to prove the following two lemmas.

LEMMA 3. *There is $\bar{T}$ such that for any $T > \bar{T}$, there is $\bar{\delta} \in (0, 1)$ such that for each $\delta \in (\bar{\delta}, 1)$, i , and ω , there is a transfer rule $U_i^{\omega, G} : H_{-i}^{T_b} \rightarrow \mathbf{R}$ that satisfies the following properties:*

- (i) $\frac{1-\delta}{1-\delta^{T_b}} G_i^{\omega}(s^x, U_i^{\omega, G}) = \bar{v}_i^{\omega}$ for all x with $x_{-i}^{\omega} = G$
- (ii) $G_i^{\omega}(s_i^{T_b}, s_{-i}^{x_{-i}}, U_i^{\omega, G}, h_i^t) \leq G_i^{\omega}(s^x, U_i^{\omega, G}, h_i^t)$ for all $s_i^{T_b}$, h_i^t , and x with $x_{-i}^{\omega} = G$
- (iii) $-(\bar{v}_i^{\omega} - \underline{v}_i^{\omega}) \leq (1 - \delta) U_i^{\omega, G}(h_{-i}^{T_b}) \leq 0$ for all $h_{-i}^{T_b}$.

To interpret this lemma, consider the complete-information game with the state ω_1 . Suppose that the opponent plays the block strategy s_i^{GG} or s_i^{GB} . That is, the opponent plans to reward player i for the state ω_1 . Statement (i) implies that if the transfer rule $U_i^{\omega_1, G}$ is appropriately chosen, then player i becomes indifferent over the prescribed block strategies, s_i^{GG} , s_i^{GB} , s_i^{BG} , and s_i^{BB} , and these strategies yield the target payoff $\bar{v}_i^{\omega_1}$ exactly. Statement (ii) requires that with this transfer rule $U_i^{\omega_1, G}$, any deviation from the prescribed strategies should not be profitable. Statement (iii) requires that this transfer be nonpositive (and bounded), that is, the transfer takes a form of welfare destruction. This last condition comes from the fact that player i 's continuation payoff at state ω , which is represented by the second term on the right-hand side of (7) and (9), is in the interval $[\underline{v}_i^{\omega}, \bar{v}_i^{\omega}]$ and, hence, below the target payoff $\bar{v}_i^{\omega}$.

As noted in the [Introduction](#), a key step in the proof is to construct a transfer rule that induces the truthful summary report while keeping the welfare destruction small. To do so, we consider a transfer rule with which the opponent makes player i indifferent over reports in the summary report round after *some* (but not all) histories. In the next subsection, we provide a sketch of the proof. The formal proof can be found in the [Appendix](#). (In the complete-information transfer game, the state ω is common knowledge, but each player i still makes an inference $\omega(i)$ and reports it, just as specified in the description of $s_i^{x_i}$. In particular, when the inference is $\omega(i) = \tilde{\omega}$, player i reports it, even though she knows that it does not coincide with the true state ω . We need to find a transfer rule under which this report is indeed incentive compatible.)

Once we have this lemma, we can construct a transition rule $\rho_{-i}^{\omega}(\cdot | G, h_{-i}^{T_b})$ that satisfies the desired properties (7) and (9) by setting

$$\rho_{-i}^{\omega}(B | G, h_{-i}^{T_b}) = -\frac{(1 - \delta) U_i^{\omega, G}(h_{-i}^{T_b})}{\bar{v}_i^{\omega} - \underline{v}_i^{\omega}}$$

for each $h_{-i}^{T_b}$. Indeed, simple algebra shows that [Lemma 3](#)(i) implies (7) and [Lemma 3](#)(ii) implies (9). [Lemma 3](#)(iii) ensures that $\rho_{-i}^{\omega}(B | G, h_{-i}^{T_b})$ defined here is indeed a probability.

The second lemma is a counterpart to [Lemma 3](#). It considers the case in which the opponent plans to punish player i (i.e., $x_{-i}^{\omega} = B$).

LEMMA 4. *There is $\bar{T}$ such that for any $T > \bar{T}$, there is $\bar{\delta} \in (0, 1)$ such that for each $\delta \in (\bar{\delta}, 1)$, i , and ω , there is a transfer rule $U_i^{\omega, B} : H_{-i}^{T_b} \rightarrow \mathbf{R}$ that satisfies the following properties:*

- (i) $\frac{1-\delta}{1-\delta^{T_b}} G_i^\omega(s^x, U_i^{\omega,B}) = \underline{v}_i^\omega$ for all x with $x_{-i}^\omega = B$
- (ii) $G_i^\omega(s_i^{T_b}, s_{-i}^{x-i}, U_i^{\omega,B}, h_i^t) \leq G_i^\omega(s^x, U_i^{\omega,B}, h_i^t)$ for all $s_i^{T_b}, h_i^t$, and x with $x_{-i}^\omega = B$
- (iii) $0 \leq (1-\delta)U_i^{\omega,B}(h_{-i}^{T_b}) \leq \bar{v}_i^\omega - \underline{v}_i^\omega$ for all $h_{-i}^{T_b}$.

The last constraint requires the transfer to be nonnegative. This comes from the fact that player i 's continuation payoff at state ω is chosen from the interval $[\underline{v}_i^\omega, \bar{v}_i^\omega]$ and is always above the target payoff $\underline{v}_i^\omega$.

It turns out that the proof of this lemma is much simpler than that of the previous lemma. In particular, we can construct a transfer rule with which the opponent makes player i indifferent over all reports in the summary report round after *every* history (just as in belief-free equilibria in Ely et al. 2005). This is analogous to Hörner and Olszewski (2006); their transfer rule for the punishment state makes a player indifferent over all actions each period of the block, while the transfer rule for the reward state has a much more complicated form. See the Appendix for the formal proof.

Again, once we have this lemma, we can construct a transition rule $\rho_{-i}^\omega(\cdot|G, h_{-i}^{T_b})$ that satisfies the desired properties (8) and (10) by setting

$$\rho_{-i}^\omega(G|B, h_{-i}^{T_b}) = \frac{(1-\delta)U_i^{\omega,B}(h_{-i}^{T_b})}{\bar{v}_i^\omega - \underline{v}_i^\omega}.$$

So Proposition 1 immediately follows once we prove the above two lemmas.

4.5 Proof sketch of Lemma 3

As noted earlier, a key step in the proof is to show that the opponent can deter a misreport of the summary inference $\omega(i)$ using a transfer, subject to the constraint that the expected welfare destruction is small. In what follows, we explain how to construct such a transfer rule. For simplicity, we assume that players do not deviate from the prescribed strategy s^x during the learning round and the main round. That is, we focus on incentives in the two report rounds.

To begin with, it is useful to point out that player i 's deviation in the summary report round can be easily deterred by making her indifferent over all summary reports, but it requires a huge welfare destruction. Let $\bar{g}_i^\omega = \max_{a \in A} |g_i^\omega(a)|$. Pick a constant C and for each block history $h_{-i}^{T_b}$, choose the transfer $\hat{U}_i^{\omega,G}(h_{-i}^{T_b})$ so that

$$\frac{1-\delta}{1-\delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) + \delta^{T_b} \hat{U}_i^{\omega,G}(h_{-i}^{T_b}) \right] = C. \quad (11)$$

That is, we choose the transfer so that player i 's total payoff is exactly C regardless of the play during the block. Then obviously player i is indifferent over all actions in each period of the block, so the truthful summary report is a best reply. Also, if we choose a small C (say, $C = -2\bar{g}_i^\omega$), we can ensure that the transfer $\hat{U}_i^{\omega,G}(h_{-i}^{T_b})$ is negative for each

$h_{-i}^{T_b}$ so that statement (iii) of the lemma holds. (From (11), the transfer $\hat{U}_i^{\omega, G}(h_{-i}^{T_b})$ is negative if the constant C is less than the average block payoff, $\frac{1-\delta}{1-\delta^{T_b}} \sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t)$.)

Unfortunately, this transfer rule $\hat{U}_i$ does not satisfy statement (i). Indeed, player i 's payoff in this transfer game is $C = -2\bar{g}_i^\omega$, which is much lower than the target payoff $\bar{v}_i^\omega$. This shows that making player i indifferent requires a huge welfare destruction.

Intuitively, this inefficiency result can be understood as follows. Consider the infinite-horizon game and suppose that the true state is ω_1 . Suppose that player i is indifferent over all summary reports in each block. Then her equilibrium payoff must be equal to her payoff when she reports $\omega(i) = \omega_2$ in every block. But this payoff must be much lower than the target payoff $\bar{v}_i^\omega$ in general, because players never agree that the true state should be ω_1 and they always choose inefficient actions.

In what follows, we show that by modifying the transfer rule above, the expected welfare destruction can be significantly reduced without affecting player i 's incentive. We do so in two steps. As a first step, we construct a transfer rule that “approximately” satisfies the desired properties; i.e., we construct a transfer rule such that the expected welfare destruction is small and the truthful summary report is an approximate best reply (but not an exact best reply) for player i . As will be seen, in this transfer rule, the opponent makes player i indifferent at some histories, but not in other cases; this helps to reduce the expected welfare destruction without affecting player i 's incentives by much. Then as a second step, we modify the transfer rule further so that the truthful summary report is an exact best reply for player i . In this second step, communication in the detailed report round plays a central role.

Step 1: Approximate incentive compatibility In this step, we construct a transfer rule such that the expected welfare destruction is small, yet the truthful summary report is an approximate best reply for player i . We first describe how to choose the transfer rule and then provide its interpretation.

- If the opponent could not make the correct inference (i.e., $\omega(-i) \neq \omega$), then choose the transfer $\tilde{U}_i^{\omega, G}(h_{-i}^{T_b})$ as in (11). This makes player i indifferent over all reports in the summary report round.
- If the opponent's signal frequency f_{-i} during player i 's learning round is not typical of ω (i.e., $|f_{-i} - \pi_{-i}^\omega(a^G)| > \varepsilon$), then choose the transfer $\tilde{U}_i^{\omega, G}(h_{-i}^{T_b})$ as in (11). Again, this makes player i indifferent over all reports in the summary report round.
- If the opponent's inference is correct ($\omega(-i) = \omega$) and if the opponent's signal frequency f_{-i} is typical of ω ($|f_{-i} - \pi_{-i}^\omega(a^G)| < \varepsilon$), then we have the following scenarios:
 - If player i reports the wrong inference $\omega(i) = \tilde{\omega}$, choose the transfer $\tilde{U}_i^{\omega, G}(h_{-i}^{T_b})$ as in (11).
 - If player i reports $\omega(i) = \omega$ or $\omega(i) = \emptyset$, choose the transfer $\tilde{U}_i^{\omega, G}(h_{-i}^{T_b})$ so that

$$\frac{1-\delta}{1-\delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) + \delta^{T_b} \tilde{U}_i^{\omega, G}(h_{-i}^{T_b}) \right] = \bar{v}_i^\omega. \quad (12)$$

That is, we set the transfer so that player i 's total payoff is exactly $\bar{v}_i^\omega$. This transfer $\tilde{U}_i^{\omega,G}(h_{-i}^{T_b})$ is still negative and satisfies statement (iii) of the lemma, because in this case, players play a^{ω,x^ω} with $x_{-i}^\omega = G$ during the main round, so that the average block payoff $\frac{1-\delta}{1-\delta^{T_b}} \sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t)$ is greater than $\bar{v}_i^\omega$.

The first two bullet points consider the case in which the opponent's observation is "irregular." Indeed, in the complete-information game with the state ω , the probability of the opponent not having the correct inference is close to 0 (Lemma 1(i)) and the probability of the signal frequency f_{-i} being not typical of ω is close to 0 (the law of large numbers). After such irregular observations, the opponent makes player i indifferent, using the huge welfare destruction (11).

The third bullet point considers the case in which the opponent's observation is "regular." In this case (given that the opponent's signal frequency f_{-i} is typical of ω), the opponent believes that player i 's signal frequency is also typical of ω and, hence, the opponent believes that player i 's inference is $\omega(i) = \omega$ or $\omega(i) = \emptyset$. (See Figure 5.) So the opponent punishes player i when her summary report is not consistent with this belief; that is, player i receives the huge negative transfer (11) if she reports the wrong inference $\omega(i) = \tilde{\omega}$. Otherwise, the opponent sets the transfer as in (12), so that player i enjoys a high payoff of $\bar{v}_i^\omega$.

Table 1 summarizes the discussions so far and describes player i 's best reply when she knows the opponent's inference $\omega(-i)$ and signal inference f_{-i} .

A point of the transfer rule above is that the huge welfare destruction (11) occurs only when the opponent's observation is irregular or player i 's summary report is irregular (i.e., $\omega(i) = \tilde{\omega}$). In the complete-information game with the state ω , these events do not occur almost surely and, hence, the expected welfare destruction is small. Indeed, player i 's expected payoff in the transfer game is approximately $\bar{v}_i^\omega$, because on the equilibrium path, the transfer (12) will be used almost surely. Hence, the above transfer rule approximately satisfies statement (i) of the lemma.

At the same time, with the transfer rule above, the truthful summary report is an approximate best reply for player i . To see this, suppose, hypothetically, that player i knows the opponent's inference $\omega(-i)$ before it is reported in the summary report round. The following lemma shows that the truthful summary report is (at least) an approximate best reply, regardless of $\omega(-i)$. This result implies that the truthful summary report is an approximate best reply, even if player i does not know $\omega(-i)$. A key in the proof is that when player i 's summary inference is $\omega(i) = \tilde{\omega}$ (which is not typical in the complete-information game with the state ω), she believes that the opponent's observation f_{-i} is not typical of ω , in which case the opponent makes her indifferent over all summary reports using the transfer rule (11). This property ensures that player i is almost indifferent

	If $ f_{-i} - \pi_{-i}^\omega(a^*) < \varepsilon$	If $ f_{-i} - \pi_{-i}^\omega(a^*) \geq \varepsilon$
If $\omega(-i) = \omega$	Report $\omega(i) = \omega$ or $\omega(i) = \emptyset$	All reports are indifferent
If $\omega(-i) \neq \omega$	All reports are indifferent	All reports are indifferent

TABLE 1. Player i 's best reply in the summary report round, given the state ω .

over all summary reports and, hence, the truthful report of $\omega(i) = \tilde{\omega}$ is an approximate best reply. Given player i 's signal frequency $f_i \in \Delta Z_i$ during her own learning round, let

$$p_i^\omega(f_i) = \sum_{f_{-i}: |\pi_{-i}^\omega(a^*) - f_{-i}| < \varepsilon} \Pr(f_{-i} | \omega, a^*, \dots, a^*, f_i),$$

that is, $p_i^\omega(f_i)$ denotes the conditional probability of the opponent's signal frequency f_{-i} being close to the ex ante distribution $\pi_{-i}^\omega(a^*)$.

LEMMA 5. *Suppose that no one has deviated from a^* during the learning round. Suppose that player i knows the opponent's inference $\omega(-i)$ before it is reported in the summary report round. If $\omega(-i) \neq \omega$, then player i is indifferent over all actions in the summary report round and, hence, the truthful summary report is a best reply for player i . If $\omega(-i) = \omega$, then the following properties hold;*

- *If player i 's inference is $\omega(i) = \omega$, the truthful summary report is a best reply.*
- *If player i 's inference is $\omega(i) = \emptyset$, the truthful summary report is a best reply.*
- *If player i 's inference is $\omega(i) = \tilde{\omega} \neq \omega$, the truthful summary report is not an exact best reply: A one-shot deviation by reporting $\omega(i) = \omega$ or $\omega(i) = \emptyset$ improves her payoff by $(\bar{v}_i^\omega + 2\bar{g}_i)p_i^\omega(f_i)$, where f_i is player i 's signal frequency during her own learning round. However, we have $p_i^\omega(f_i) < \exp(-T^{\frac{1}{2}})$, so the truthful summary report is an approximate best reply when T is large.*

PROOF. From the last row of [Table 1](#), it is clear that player i is indifferent over all actions when $\omega(-i) \neq \omega$. So we focus on the case in which $\omega(-i) = \omega$.

Case 1: Player i 's inference is $\omega(i) = \omega$. From [Table 1](#), reporting $\omega(i) = \omega$ is a best reply regardless of f_{-i} . Hence, the truthful report of $\omega(i) = \omega$ is an exact best reply, regardless of player i 's belief about f_{-i} .

Case 2: Player i 's inference is $\omega(i) = \emptyset$. For the same reason, reporting $\omega(i) = \emptyset$ truthfully is a best reply for player i regardless of her belief.

Case 3: Player i 's inference is $\omega(i) = \tilde{\omega} \neq \omega$. Note that player i believes that $|f_{-i} - \pi_{-i}^\omega(a^*)| \geq \varepsilon$ with probability $1 - p_i^\omega(f_i)$ and that $|f_{-i} - \pi_{-i}^\omega(a^*)| < \varepsilon$ with probability $p_i^\omega(f_i)$. From [Table 1](#), player i is indifferent over all summary reports in the former case. However, in the latter case, the truthful summary report is not a best reply; the truthful report of $\omega(i) = \tilde{\omega}$ leads to the huge negative transfer (11) and yields a payoff of $-2\bar{g}_i^\omega$, while reporting $\omega(i) = \omega$ or $\omega(i) = \emptyset$ leads to the transfer (12) and yields a payoff of $\bar{v}_i^\omega$. So the expected gain by reporting $\omega(i) = \omega$ or $\omega(i) = \emptyset$ is indeed $(\bar{v}_i^\omega + 2\bar{g}_i)p_i^\omega(f_i)$.

Now, recall that from [Lemmas 1\(iii\) and 2](#), whenever player i 's inference is $\omega(i) = \tilde{\omega}$, we have $p_i^\omega(f_i) < \exp(-T^{\frac{1}{2}})$. Hence, the expected gain above converges to 0 as $T \rightarrow \infty$. $\square$

A few comments are in order. First, under the transfer rule U_i^ω above, reporting the null inference $\omega(i) = \emptyset$ is “executed” in the sense that it always yields the same payoff as the one by reporting the correct inference $\omega(i) = \omega$ and, hence, always a best reply in

the complete-information game with the state ω . Since we choose such a transfer rule U_i^ω for each state ω , reporting the null inference $\omega(i) = \emptyset$ is a best reply regardless of the state ω , of the opponent's inference $\omega(-i)$, and of the opponent's signal frequency f_{-i} . This property is useful to solve the problem raised in [Remark 2](#), because even if player i has conflicting beliefs about the opponent's beliefs at different states (recall the point C in [Figure 6](#) in the [Introduction](#)), reporting the null inference $\omega(i) = \emptyset$ is a best reply for player i at both states.

Second, for the above argument to work, it is crucial that player i 's inference rule is chosen in such a way that the set of player i 's observations that induce the inference $\omega(i) = \omega$ is isolated with the one that induces the inference $\omega(i) = \tilde{\omega}$. That is, the two circles in [Figure 5](#) are disjoint, and there is no “knife-edge” case in which player i 's inference switches from $\omega(i) = \omega_1$ to $\omega(i) = \omega_2$. This property, together with the correlated learning condition ([Condition 3](#)), ensures that the opponent can almost perfectly distinguish whether player i 's inference is $\omega(i) = \omega$ or $\omega(i) = \tilde{\omega}$. Indeed, conditional on the state ω , the opponent's signal frequency f_{-i} is typical of ω almost surely given that player i has the correct inference $\omega(i) = \omega$, while f_{-i} is not typical of ω almost surely given that player i has the wrong inference $\omega(i) = \tilde{\omega}$. So if player i deviates by reporting $\omega(i) = \omega$ when the true inference is $\omega(i) = \tilde{\omega}$, the opponent can detect this misreport almost surely. This property is useful to deter player i 's misreport, while keeping the expected welfare destruction small.

Step 2: Exact incentive compatibility The transfer rule $\tilde{U}_i^{\omega, G}$ in the previous step does not ensure that the truthful summary report is a best reply. Specifically, when player i has the wrong inference $\omega(i) = \tilde{\omega}$, she can improve her payoff by misreporting. So to satisfy statement (ii) of the lemma, we need to modify the transfer rule further. The idea is to give a “bonus” to player i when she reports the wrong inference $\omega(i) = \tilde{\omega}$. This gives an extra incentive to report $\omega(i) = \tilde{\omega}$ truthfully.

As in the previous step, we first explain how to choose the transfer rule and then provide its interpretation. Recall that in the detailed report round, player i reports her full signal sequence $(z_i^t)_{t \in T(i)}$ during her own learning round. Let $(\hat{z}_i^t)_{t \in T(i)}$ denote the reported signal sequence and let $\hat{f}_i \in \Delta Z_i$ denote the signal frequency computed from this sequence; that is, $\hat{f}_i(z_i) = \frac{|\{t \in T(i) | \hat{z}_i^t = z_i\}|}{T}$. Let $e(z_i)$ denote the $|Z_i|$ -dimensional column vector where the component corresponding to z_i is 1 and the remaining components are 0. Similarly, let $e(z_{-i})$ denote the $|Z_{-i}|$ -dimensional column vector where the component corresponding to z_{-i} is 1 and the remaining components are 0. We define the transfer rule $U_i^{\omega, G}$ as follows:

- If the opponent could not make the correct inference (i.e., $\omega(-i) \neq \omega$), then choose the transfer $U_i^{\omega, G}(h_{-i}^{T_b})$ as in [\(11\)](#). This makes player i indifferent over all reports in the summary report round.
- If the opponent's inference is correct ($\omega(-i) = \omega$), then the following scenarios occur:

– If player i reports $\omega(i) = \omega$ or $\omega(i) = \emptyset$, set

$$U_i^{\omega, G}(h_{-i}^{T_b}) = \tilde{U}_i^{\omega, G}(h_{-i}^{T_b}) - \frac{1 - \delta^{T_b}}{\delta^{T_b}(1 - \delta)} \frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2.$$

– If player i reports $\omega(i) = \tilde{\omega}$, set

$$U_i^{\omega, G}(h_{-i}^{T_b}) = \tilde{U}_i^{\omega, G}(h_{-i}^{T_b}) + \frac{1 - \delta^{T_b}}{\delta^{T_b}(1 - \delta)} \left(b_i^\omega(\hat{f}_i) - \frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2 \right),$$

where

$$b_i^\omega(\hat{f}_i) = \begin{cases} (\bar{v}_i^\omega + 2\bar{g}_i)p_i^\omega(f_i) & \text{if } |\hat{f}_i - \pi_i^{\tilde{\omega}}(a^G)| < \varepsilon \\ 0 & \text{otherwise.} \end{cases}$$

Compared to the transfer rule $\tilde{U}_i^{\omega, G}$ in the previous subsection, here we have two new terms, $b_i^\omega(\hat{f}_i)$ and $\frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$. Very roughly speaking, the term $b_i^\omega(\hat{f}_i)$ helps to provide truthful incentives in the summary report round, while the term $\frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$ helps to provide truthful incentives in the detailed report round. In what follows, we explain this transfer rule in more detail.

The first bullet point considers the case in which the opponent does not have the correct inference. In this case, we choose the transfer rule just as in the previous step, that is, the transfer is chosen so that regardless of player i 's play, her payoff in the transfer game is $C = -2\bar{g}_i^\omega$. This implies that if player i can observe the opponent's inference $\omega(-i)$ and if $\omega(-i) \neq \omega$, then she is indifferent over all summary reports, just as in [Lemma 5](#).

The second bullet point considers the case in which the opponent has the correct inference $\omega(-i) = \omega$. In this case, if the transfer rule $\tilde{U}_i^{\omega, G}$ in the previous step is used, the truthful report of $\omega(i) = \tilde{\omega}$ is suboptimal; indeed, as shown in [Lemma 5](#), reporting $\omega(i) = \omega$ or $\omega(i) = \emptyset$ improves her payoff by $(\bar{v}_i^\omega + 2\bar{g}_i)p_i^\omega(f_i)$. To fix this problem, we give a bonus payment $b_i^\omega(\hat{f}_i)$ to player i when she reports $\omega(-i) = \tilde{\omega}$. For simplicity, assume for now that player i is truthful in the detailed report round so that $\hat{f}_i = f_i$. When $|f_i - \pi_i^{\tilde{\omega}}(a^G)| < \varepsilon$, we set the amount of the bonus equal to the expected gain by misreporting in the summary report round, $(\bar{v}_i^\omega + 2\bar{g}_i)p_i^\omega(f_i)$. This makes player i indifferent over all reports in the summary report round, so the truthful summary report becomes an exact best reply. See the shaded area in [Figure 7](#).

By contrast, when $|f_i - \pi_i^{\tilde{\omega}}(a^G)| \geq \varepsilon$, we set $b_i^\omega(f_i) = 0$. That is, we do not pay a bonus payment even if player i reports $\omega(i) = \tilde{\omega}$. This is so because in this case, [Lemma 1](#) (iii) ensures that player i 's true inference must be either $\omega(i) = \omega$ or $\omega(i) = \emptyset$; so if player i reports $\omega(i) = \tilde{\omega}$, it should be regarded as a misreport, and we do not pay a bonus payment.

Thanks to the bonus payment above, the truthful summary report becomes an exact best reply, provided that player i is truthful in the detailed report round. However, given

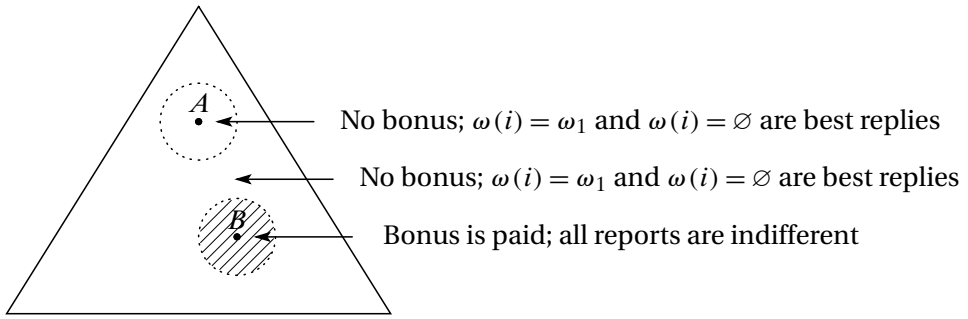


FIGURE 7. Player i 's incentive in the complete-information game with ω_1 , assuming that $f_i = \hat{f}_i$.

the specification of the bonus function b_i^ω above, player i may want to misreport in the detailed report round. Indeed, since the bonus payment $b_i^\omega(\hat{f}_i)$ depends on player i 's detailed report $\hat{f}_i$, she may want to manipulate $\hat{f}_i$ so as to maximize this bonus payment $b_i^\omega(\hat{f}_i)$.

To deter such a misreport in the detailed report round, we have the additional term $\frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$ in the transfer $U_i^{\omega, G}$. To better understand this term, note that $C_i^\omega(a^*)e(\hat{z}_i^t)$ is player i 's *forecast* about the opponent's signal distribution in period t when she observed $\hat{z}_i^t$ in that period. By contrast, the term $e(z_{-i}^t)$ is the *actual realization* of the opponent's signal. It turns out that if player i misreports $\hat{z}_i^t$, then the difference $|e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$ between the forecast and the realization becomes larger, which decreases the amount of the transfer. This provides an extra incentive to report z_i^t truthfully in the detailed report round, and this effect is of order $\frac{1}{T}$, as the coefficient on this term is $\frac{\varepsilon}{T}$. By contrast, the gain by misreporting z_i^t is at most of order $O(\exp(-T^{\frac{1}{2}}))$, because Lemma 2 ensures that the bonus payment is of order $O(\exp(-T^{\frac{1}{2}}))$. Since the former effect is larger than the latter, player i indeed reports truthfully in the detailed report round. See Lemma 10 in the formal proof for more details.

So far we have explained that the transfer rule above induces right incentives in the two (both summary and detailed) report rounds. Note also that we have made only a small change in the transfer rule relative to the one in the previous step; indeed, the two new terms, $b_i^\omega(\hat{f}_i)$ and $\frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$, are quite small. Accordingly, player i 's payoff in the transfer game is still approximately the target payoff $\bar{v}_i^\omega$, so that statement (i) of the lemma is approximately satisfied. So by adding a small constant term to the transfer, we can satisfy statement (i) of the lemma exactly. More details are given in the formal proof.

APPENDIX: PROOFS OF LEMMAS

A.1 Proof of Lemma 1

We formally explain how each player i forms the inference $\omega(i)$ from her history h_i^T in the learning round. We introduce three different scoring rules: a base score, a random

score, and a final score. Then we explain how these scores are converted to the inference $\omega(i)$ and show that the resulting inference rule satisfies all the desired conditions.

Step 1: Base score.

For simplicity, we first consider the case in which no one deviates from a^* during player i 's learning round. Let $f_i(a^*) = (f_i(a^*)[z_i])_{z_i \in Z_i} \in \Delta Z_i$ denote player i 's signal frequency during this round. Given a signal frequency $f_i(a^*)$, we compute a *base score* $q_i^{\text{base}} \in \mathbb{R}^{|Z_i|}$ using the formula

$$q_i^{\text{base}} = Q_i(a^*)f_i(a^*).$$

Here $Q_i(a^*)$ is a $|Z_i| \times |Z_i|$ matrix, so it is a linear operator that maps a signal frequency $f_i(a^*) \in \Delta Z_i$ to a score vector $q_i^{\text{base}} \in \mathbb{R}^{|Z_i|}$. (Here both $f_i(a^*)$ and q_i^{base} are column vectors.) The specification of the matrix $Q_i(a^*)$ is given later. From the law of large numbers, if the true state were ω , the score q_i^{base} should be close to the expected score $Q_i(a^*)\pi_i^\omega(a^*)$ almost surely. So if we choose a matrix such that $Q_i(a^*)\pi_i^{\omega_1}(a^*) \neq Q_i(a^*)\pi_i^{\omega_2}(a^*)$, then player i can distinguish ω_1 from ω_2 using the base score.

If someone deviates from a^* during the learning round, the base score is computed by a slightly different formula. Given a history $h_i^T = (a^t, z_i^t)_{t=1}^T$ in player i 's learning round, let $\beta(a)$ denote the frequency of an action profile a during the round, that is, let $\beta(a) = \frac{|\{t \in \{1, \dots, T\} | a^t = a\}|}{T}$ for each a . Also, let $f_i(a) \in \Delta Z_i$ denote the signal frequency for periods in which the profile a was played, that is, $f_i(a) = (f_i(a)[z_i])_{z_i \in Z_i}$, where $f_i(a)[z_i] = \frac{|\{t \in \{1, \dots, T\} | (a^t, z_i^t) = (a, z_i)\}|}{T\beta(a)}$. For a that was not played during the T periods, we set $f_i(a) = 0$. We define the base score as

$$q_i^{\text{base}} = \sum_{a \in A} \beta(a) Q_i(a) f_i(a),$$

where for each a , $Q_i(a)$ is a $|Z_i| \times |Z_i|$ matrix that is specified later. In words, player i computes the score vector $q_i^{\text{base}}(a) = Q_i(a)f_i(a)$ for each action profile a and takes a weighted average of these scores over all a . Note that this formula reduces to the previous one when no one deviates from a^* .

We choose the matrices $Q_i(a)$ as in the following lemma. (This lemma specifies the matrix $Q_i(a)$ only for a with $a_{-j} = a_{-j}^*$; for other a , let $Q_i(a)$ be the normal matrix.)

LEMMA 6. *Suppose that [Condition 2](#) holds. Then for each i , there are $|Z_i|$ -dimensional column vectors $q_i^{\omega_1}$ and $q_i^{\omega_2}$ with $q_i^{\omega_1} \neq q_i^{\omega_2}$ such that for each $j \neq i$ and a_j , there is a full-rank matrix $Q_i(a_j, a_{-j}^*)$ such that*

$$Q_i(a_j, a_{-j}^*)\pi_i^\omega(a_j, a_{-j}^*) = \begin{cases} q_i^{\omega_1} & \text{if } \omega = \omega_1 \\ q_i^{\omega_2} & \text{if } \omega = \omega_2. \end{cases}$$

The proof directly follows from [Condition 2](#).

That is, we choose the matrices $Q_i(a)$ so that if the true state is ω , the expected base score is q_i^ω regardless of the opponent's actions during the learning round. Since $q_i^{\omega_1} \neq q_i^{\omega_2}$, player i can indeed distinguish the true state using the base score.

While the opponent's action cannot influence the expected value of the base score, it may still influence the *distribution* of player i 's base score. Thus, if player i uses the base score to distinguish the true state, player j may be able to manipulate player i 's inference by deviating from a^* , so that statement (ii) of the lemma fails. In the next step, we modify the scoring rule to avoid this problem.

Step 2: Random score.

Let $Q_i(a)$ be as in Lemma 6 and for each z_i , let $q_i(a, z_i)$ be the column of the matrix $Q_i(a)$ corresponding to signal z_i . Note that $q_i(a, z_i)$ is a $|Z_i|$ -dimensional column vector, so let $q_{i,k}(a, z_i)$ denote its k th component. Without loss of generality, we assume that each entry of the matrix $Q_i(a)$ is in the interval $[0, 1]$, i.e., we assume that $q_{i,k}(a, z_i) \in [0, 1]$.¹⁸

For each (a, z_i) , let $\kappa_i(a, z_i) \in \{0, 1\}^{|Z_i|}$ be a random variable such that each component is randomly and independently drawn from $\{0, 1\}$, and such that for each k , the probability of the k th component being 1 is $q_{i,k}(a, z_i)$. Note that given (a, z_i) , the expected value of this random variable $\kappa_i(a, z_i)$ is exactly equal to $q_i(a, z_i)$.

Let $h_i^T = (a^t, z_i^t)_{t=1}^T$ denote player i 's history during her learning round. Given such a history h_i^T , define the *random score* $q_i^{\text{random}} \in \mathbb{R}^{|Z_i|}$ as

$$q_i^{\text{random}} = \frac{1}{T} \sum_{t=1}^T \kappa_i(a^t, z_i^t).$$

That is, we generate independent random variables $(\kappa_i(a^t, z_i^t))_{t=1}^T$ for each period- t outcome (a^t, z_i^t) and define the random score as its average.

Note that for a given history h_i^T during the learning round, the expected value of the random score is exactly equal to the base score. This, together with the law of large numbers, implies that if the true state is ω , the random score is close to q_i^ω almost surely; hence, player i can distinguish the state using the random score. Also, by the construction, the opponent's action cannot influence the distribution of player i 's random score. (Here we use Lemma 6, which ensures that the expected value of the base score does not depend on the opponent's actions.) This implies that if player i uses the random score to distinguish the true state, then player j cannot manipulate player i 's inference at all.

However, the random score is not a sufficient statistic of player i 's signal frequency f_i . For example, even when the base score is close to q_i^ω so that the signals indicate that ω is likely to be the true state, if there are too many unlucky draws of the random variables $\kappa_i(a^t, z_i^t)$, the random scores can be far away from q_i^ω . Accordingly statement (iii) does not hold if player i uses the random score to make the inference. In the next step, we introduce the notion of the final score to fix this problem.

Step 3: Final score.

Now we introduce the concept of a final score, which combines the advantages of the base score and the random score. Let $\tilde{\varepsilon} > 0$ be a small number. Player i 's *final score* q_i^{final}

¹⁸If some entry of $Q_i(a)$ is not in $[0, 1]$, we consider the affine transformation of $q_i(a, z_i)$, $q_i^{\omega_1}$, and $q_i^{\omega_2}$ so that each entry is in $[0, 1]$.

is defined as

$$q_i^{\text{final}} = \begin{cases} q_i^{\text{random}} & \text{if } |q_i^{\text{random}} - q_i^{\text{base}}| < \tilde{\varepsilon} \\ q_i^{\text{base}} & \text{otherwise.} \end{cases}$$

In words, if the random score is close to the base score, it is used as the final score. Otherwise, the base score is used as the final score.

By the definition, the final score is always close to the base score. This means that player i 's final score is an “almost sufficient” statistic for her T -period private history.

Another important property of the final score is that a player's action cannot influence the opponent's score almost surely. To see this, note that conditional on the T -period history $(a^t, z_i^t)_{t=1}^T$, the expected value of the random score q_i^{random} is equal to the base score q_i^{base} . This implies that with probability close to 1, the random score is close to the base score and, hence, the final score is equal to the random score, which does not depend on the opponent's deviation. Formally, for any $\tilde{\varepsilon} > 0$, there is $\bar{T}$ such that for any $T > \bar{T}$, in any period of the learning round, the probability that the opponent's action can influence player i 's final score is less than $\exp(-T^{\frac{1}{2}})$.

Step 4: From the final score to the inference.

Now we describe how each player i makes the inference $\omega(i)$. Recall that $\tilde{\varepsilon} > 0$ is a small number. We set $\omega(i) = \omega_1$ if

$$|q_i^{\omega_1} - q_i^{\text{final}}| < 2\tilde{\varepsilon} \quad (13)$$

and we set $\omega(i) = \omega_2$ if

$$|q_i^{\omega_2} - q_i^{\text{final}}| < 2\tilde{\varepsilon}. \quad (14)$$

If neither (13) nor (14) holds, then we set $\omega(i) = \emptyset$. In words, if the score is in the $2\tilde{\varepsilon}$ neighborhood of the expected score at ω , then we set $\omega(i) = \omega$. Note that the inference $\omega(i)$ is indeed well defined if $\tilde{\varepsilon}$ is sufficiently small.

Now we show that this inference rule satisfies all the desired properties. Statement (i) is simply a consequence of the law of large numbers. Statement (ii) follows from the fact that the opponent's deviation cannot influence player i 's final score almost surely.

To prove statement (iii), suppose that no one deviates from a^* , and pick a signal frequency f_i such that player i will choose $\omega(i) = \omega$ with positive probability. By the definition of the final score, given this signal frequency f_i , the resulting final score is always within $\tilde{\varepsilon}$ of the base score q_i^{base} , which is equal to $Q_i(a^*)f_i$. Hence, from (13) and (14), we must have

$$|q_i^\omega - Q_i(a^*)f_i| < 3\tilde{\varepsilon}.$$

Since $Q_i(a^*)$ has a full rank, this implies

$$|\pi_i^\omega(a^*) - f_i| < K\tilde{\varepsilon}$$

for some constant $K > 0$. Hence, statement (iii) follows.

A.2 Proof of Lemma 3

As in Section 4.5, we first construct a transfer rule $\tilde{U}_i^{\omega, G}$ that approximately satisfies statement (ii) of the lemma. That is, we construct $\tilde{U}_i^{\omega, G}$ such that playing the prescribed strategy $s_i^{x_i}$ is a best reply for player i except in the summary report round, and it is an “approximate” best reply in the summary report round. Then we modify this transfer rule $\tilde{U}_i^{\omega, G}$ and construct a new transfer rule $U_i^{\omega, G}$ that satisfies statement (ii) exactly. Then we show that the modified transfer rule $U_i^{\omega, G}$ satisfies statements (i) and (iii) as well.

We begin by introducing the notion of *regular histories*. We first give the definition and then give its interpretation. A block history $h_{-i}^{T_b}$ is *regular given* (ω, G) if it satisfies all the following conditions:

- (G1) Players choose a^* in the learning round.
- (G2) In the summary report round, the opponent reports $\omega(-i) = \omega$ and player i reports $\omega(i) = \omega$ or $\omega(i) = \emptyset$.
- (G3) The opponent reports $x_{-i}^\omega = G$ in the first period of the main round.
- (G4) Players follow the prescribed strategy in the second or later periods of the main round.
- (G5) The opponent's signal frequency f_{-i} during player i 's learning round is close to the ex ante distribution $\pi_{-i}^\omega(a^*)$, i.e., $|f_{-i} - \pi_{-i}^\omega(a^*)| < \varepsilon$.

A history $h_{-i}^{T_b}$ is *irregular given* (ω, G) if it is not regular.

Roughly, a history is regular if (i) no one makes an observable deviation from the prescribed strategy s^x , (ii) no one reports a wrong inference, and (iii) the opponent's signal frequency f_{-i} is typical of ω . Note that this concept is an extension of “regular observations” briefly discussed in Section 4.5; now we allow players' deviations in the learning and the main round, and we call the history irregular if such a deviation occurs.

Step 1: Construction of $\tilde{U}_i^{\omega, G}$ Choose a transfer rule $\tilde{U}_i^{\omega, G} : H_{-i}^{T_b} \rightarrow \mathbf{R}$ such that the following statements hold.

- If the history $h_{-i}^{T_b}$ is regular given (ω, G) , choose $\tilde{U}_i^{\omega, G}(h_{-i}^{T_b})$ so that it solves

$$\frac{1 - \delta}{1 - \delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) + \delta^{T_b} \tilde{U}_i^{\omega, G}(h_{-i}^{T_b}) \right] = \bar{v}_i^\omega. \quad (15)$$

- If the history $h_{-i}^{T_b}$ is irregular, choose $\tilde{U}_i^{\omega, G}(h_{-i}^{T_b})$ so that

$$\frac{1 - \delta}{1 - \delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) + \delta^{T_b} \tilde{U}_i^{\omega, G}(h_{-i}^{T_b}) \right] = -2\bar{g}_i^\omega. \quad (16)$$

In words, if (i) no one makes an observable deviation, (ii) no one reports a wrong inference, and (iii) the opponent's observation f_{-i} is typical of ω , then the transfer $U_i^{\omega, G}$ is

chosen in such a way that player i 's payoff in the complete-information transfer game is exactly the target payoff $\bar{v}_i^\omega$. By Contrast, if player i makes an observable deviation or reports a wrong inference or if the opponent's observation is not typical of ω , then we give a huge negative transfer to player i so that the payoff goes down to $-2\bar{g}_i^\omega$. Note that this transfer rule is very similar to the one in Section 4.5; the only difference is that player i receives a huge negative transfer when there is a deviation in the learning round or in the main round. So (assuming that no one has deviated in the learning round) player i 's best reply in the summary report round is still as in Table 1 in Section 4.5.

Step 2: $\tilde{U}_i^{\omega, G}$ approximately satisfies statement (ii) Consider the complete-information transfer game with the state ω and the transfer rule $\tilde{U}_i^{\omega, G}$ above. Suppose that the opponent's current plan is x_{-i} with $x_{-i}^\omega = G$. We show that the prescribed strategies s_i^{GG} , s_i^{GB} , s_i^{BG} , and s_i^{BB} are approximate best replies for player i . We first show that the strategies s_i^{GG} , s_i^{GB} , s_i^{BG} , and s_i^{BB} are exact best replies except in the summary report round.

LEMMA 7. *In the learning round, the main round, and the detailed report round, the strategies s_i^{GG} , s_i^{GB} , s_i^{BG} , and s_i^{BB} are best replies for player i , regardless of the past history.*

PROOF. Actions in the detailed report round and in the first period of the main round do not influence whether the resulting history is regular or not. Hence, player i is indifferent over all actions in these periods.

In the learning round and the second or later periods of the main round, player i prefers not to deviate from the prescribed strategy $s_i^{x_i}$. This is so because such deviations are observable and make the history irregular for sure, which yields the worst payoff, $-2\bar{g}_i^\omega$. $\square$

In what follows, we focus on the incentive problem in the summary report round. The next lemma shows that if someone has deviated during the learning round, then the truthful summary report is an exact best reply.

LEMMA 8. *Suppose that someone has deviated from a^* during the learning round. Then player i is indifferent over all actions in the summary report round and, hence, the truthful summary report is a best reply.*

PROOF. If someone has deviated from a^* in the learning round, then the opponent's history $h_{-i}^{T_h}$ becomes irregular regardless of player i 's summary report. Hence, player i is indifferent over all summary reports. $\square$

Now consider the case in which no one has deviated during the learning round. In this case, Lemma 5 still holds, because the transfer rule constructed above is exactly the same as the one in Section 4.5. So the truthful summary report is indeed an approximate best reply.

Step 3: Construction of $U_i^{\omega, G}$ and statement (ii) As explained, the transfer rule $\tilde{U}_i^{\omega, G}$ approximately satisfies statement (ii) of [Lemma 3](#), but not exactly. Indeed, as shown in [Lemma 5](#), the truthful report of $\omega(i) = \tilde{\omega}$ in the summary report round is not an exact best reply. So we modify the transfer rule $\tilde{U}_i^{\omega, G}$ in such a way that (ii) holds exactly. The idea here is very similar to the one presented in Step 2 in [Section 4.5](#); we give a “bonus” to player i when she reports the incorrect inference $\omega(i) = \tilde{\omega}$, which gives her an extra incentive to report $\omega(i) = \tilde{\omega}$ truthfully.

Define a *bonus function* $b_i^\omega : H_{-i}^{T_b} \rightarrow \mathbf{R}$ as

$$b_i^\omega(h_{-i}^{T_b}) = \begin{cases} 0 & \text{if player } i \text{ reports } \omega(i) = \omega \text{ or } \omega(i) = \emptyset \\ 0 & \text{if someone deviates in the learning round} \\ 0 & \text{if } \omega(-i) \neq \omega \\ 0 & \text{if } |\hat{f}_i - \pi_i^{\tilde{\omega}}(a^*)| \geq \varepsilon \\ (\bar{v}_i^\omega + 2\bar{g}_i^\omega)p_i^\omega(\hat{f}_i) & \text{otherwise.} \end{cases}$$

This bonus function is the same as the one in [Section 4.5](#) except that we specify values for the case in which someone makes observable deviations. Recall that the amount of the bonus by reporting $\omega(i) = \tilde{\omega}$ is $(\bar{v}_i^\omega + 2\bar{g}_i^\omega)p_i^\omega(\hat{f}_i)$, which is exactly equal to the expected gain by misreporting in the summary report round ([Lemma 5](#)). This makes player i indifferent over all reports in the summary report round and, thus, the truthful report of $\omega(i) = \tilde{\omega}$ becomes a best reply.

The following lemma shows that the amount of the bonus, $b_i^\omega(h_{-i}^{T_b})$, is very small regardless of the opponent’s history $h_{-i}^{T_b}$. To obtain this lemma, it is crucial that we pay a bonus only if $|\hat{f}_i - \pi_i^{\tilde{\omega}}(a^*)| < \varepsilon$; this condition ensures that $p_i^\omega(\hat{f}_i)$ is small and so is the bonus.

LEMMA 9. *There is $\bar{T}$ such that for any $T > \bar{T}$ and $h_{-i}^{T_b}$, we have $b_i^\omega(h_{-i}^{T_b}) < 3\bar{g}_i^\omega \exp(-T^{\frac{1}{2}})$.*

PROOF. [Lemma 2](#) implies that whenever $|\hat{f}_i - \pi_i^{\tilde{\omega}}(a^*)| < \varepsilon$, we have $p_i^\omega(\hat{f}_i) < \exp(-T^{\frac{1}{2}})$. Then by the definition of b_i^ω , we obtain the lemma. $\square$

Now we define the new transfer rule $U_i^{\omega, G}$ as

$$U_i^{\omega, G}(h_{-i}^{T_b}) = \tilde{U}_i^{\omega, G}(h_{-i}^{T_b}) + \frac{1 - \delta^{T_b}}{\delta^{T_b}(1 - \delta)} \left(c^G + b_i^\omega(h_{-i}^{T_b}) - \frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2 \right),$$

where c^G is a constant term that is specified later. Again the specification of the transfer rule is very similar to the one in [Section 4.5](#); a key is that we add the terms $b_i^\omega(h_{-i}^{T_b})$ and $\frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$ to provide the right incentives in the two report rounds.

In what follows, we verify that this transfer rule indeed satisfies statement (ii) of the lemma. That is, the prescribed strategy $s_i^{x_i}$ is a best reply in the transfer game. The following lemma considers incentives in the detailed report round:

LEMMA 10. *There is $\bar{T} > 0$ such that for any $T > \bar{T}$, the truthful report in the detailed report round is a best reply for player i regardless of the past history. In particular, the truthful report is a best reply even if player i has misreported in the summary report round.*

PROOF. Recall that under the transfer rule $\tilde{U}_i^{\omega, G}$, player i is indifferent over all actions in the detailed report round. (This is so because her actions in the detailed report round cannot influence whether the opponent's history is regular.) Thus, it is sufficient to check how player i 's deviation in the detailed report round influences the additional terms, $b_i^\omega(h_{-i}^{T_b}) - \frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$.

In the detailed report round, player i reports the signals $(z_i^t)_{t \in T(i)}$ during her own learning round and the signals $(z_i^t)_{t \in T(-i)}$ during the opponent's learning round. It is easy to see that the truthful report of $(z_i^t)_{t \in T(-i)}$ is a best reply for player i , because this report does not influence the additional terms above. So what remains is to show that the truthful report of the signals $(z_i^t)_{t \in T(i)}$ during her own learning round is a best reply for player i .

Pick some $t \in T(i)$, and suppose that player i deviates by reporting a signal $\tilde{z}_i \neq z_i^t$ such that $C_i^\omega(a^*)e(z_i^t) \neq C_i^\omega(a^*)e(\tilde{z}_i)$; that is, consider a misreport $\tilde{z}_i$ such that the corresponding posterior distribution of z_{-i} differs from the true posterior distribution $C_i^\omega(a^*)e(z_i^t)$. This misreport increases the expected value of $|e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$ and, hence, reduces the expected transfer.¹⁹ This effect is of order $\frac{1}{T}$, as we have the coefficient $\frac{\varepsilon}{T}$. This implies that this misreport is not profitable, as the gain is at most of order $\exp(-T^{\frac{1}{2}})$ from Lemma 9.

Next suppose that player i deviates by reporting a signal $\tilde{z}_i \neq z_i^t$ such that $C_i^\omega(a^*) \times e(z_i^t) = C_i^\omega(a^*)e(\tilde{z}_i)$. In this case, player i 's payoff is the same as the one when she does not deviate; indeed, this misreport does not change $b_i^\omega(h_{-i}^{T_b})$ or $|e(\hat{z}_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$. Hence, this misreport is not profitable. $\square$

The next lemma shows that thanks to the bonus function b_i^ω , the truthful report in the summary report round is an exact best reply. This implies that the modified transfer $U_i^{\omega, G}$ satisfies Lemma 3(ii).

LEMMA 11. *The truthful report in the summary report round is a best reply for player i , regardless of the past history.*

PROOF. Throughout the proof, we assume that player i is truthful in the detailed report round, since we have Lemma 10. Suppose, hypothetically, that player i knows the opponent's inference $\omega(-i)$ before it is revealed in the summary report round. We show that

¹⁹Indeed, as explained in Section 4.2 of Kandori and Matsushima (1998), we have

$$\sum_{z_{-i} \in Z_{-i}} C_i^\omega(a^*)e(z_i^t)[z_{-i}]|e(z_{-i}) - C_i^\omega(a^*)e(z_i^t)|^2 < \sum_{z_{-i} \in Z_{-i}} C_i^\omega(a^*)e(z_i^t)[z_{-i}]|e(z_{-i}) - C_i^\omega(a^*)e(\tilde{z}_i^t)|^2$$

for this misreport $\tilde{z}_i^t$, so the expected transfer indeed decreases. Note that the opponent's block strategy does not depend on the signal z_{-i}^t , so regardless of the opponent's past actions, player i 's posterior belief about z_{-i}^t is indeed $C_i^\omega(a^*)e(z_i^t)$.

the truthful report of $\omega(i)$ is a best reply for player i regardless of $\omega(-i)$. This implies that the truthful report is a best reply even if player i does not know $\omega(-i)$; hence, the result.

First, suppose that someone deviated from a^* in the learning round or the opponent's inference is $\omega(-i) \neq \omega$. In these cases, the bonus payment is 0 regardless of player i 's summary report. Also, from Lemmas 8 and 5, player i is indifferent over all actions in the summary report round with the transfer $\tilde{U}_i^{\omega, G}$. Hence, player i is indifferent over all actions in the summary report round even with the new transfer rule, and the truthful report is a best reply.

Next suppose that no one has deviated in the learning round and that the opponent's inference is $\omega(-i) = \omega$. There are two cases to be considered.

Case 1: Player i 's signal frequency f_i during her own learning round is such that $|\pi_i^{\tilde{\omega}}(a^) - f_i| \geq \varepsilon$.* In this case, from Lemma 1(iii), player i 's inference must be either $\omega(i) = \omega$ or $\omega(i) = \emptyset$. Then from Lemma 5, the truthful report of $\omega(i)$ in the summary report round is a best reply under the transfer rule $\tilde{U}_i^{\omega, G}$. The same result holds even under the new transfer $U_i^{\omega, G}$, because given that $|\pi_i^{\tilde{\omega}}(a^*) - f_i| \geq \varepsilon$, the bonus payment b_i^ω is 0 regardless of player i 's summary report.

Case 2: Player i 's signal frequency f_i during her own learning round is such that $|\pi_i^{\tilde{\omega}}(a^) - f_i| < \varepsilon$.* We claim that in this case, player i is indifferent over all summary reports (and, hence, the truthful report of $\omega(i)$ is a best reply). Under the transfer rule $\tilde{U}_i^{\omega, G}$, reporting $\omega(i) = \omega$ yields an expected payoff of $p_i^\omega(f_i)\bar{v}_i^\omega + (1 - p_i^\omega(f_i))(-2\bar{g}_i^\omega)$, since the probability of the block history being regular is $p_i^\omega(f_i)$. The same is true when player i reports $\omega(i) = \emptyset$. By contrast, when player i reports $\omega(i) = \tilde{\omega}$, the block history is always irregular and, hence, the expected payoff is $-2\bar{g}_i^\omega$. Obviously this payoff is worse than the payoff by reporting $\omega(i) = \omega$, and the payoff difference is

$$(p_i^\omega(f_i)\bar{v}_i^\omega + (1 - p_i^\omega(f_i))(-2\bar{g}_i^\omega)) - 2\bar{g}_i^\omega = (\bar{v}_i^\omega + 2\bar{g}_i^\omega)p_i^\omega(f_i).$$

Now consider the modified transfer $U_i^{\omega, G}$ with which player i can obtain the bonus b_i^ω by reporting $\tilde{\omega}$ in the summary report round. Since the amount of the bonus is precisely equal to the payoff difference above, player i is indifferent over all summary reports, as desired. $\square$

Step 4: Proof of statement (i) In what follows, we show that the transfer rule $U_i^{\omega, G}$ satisfies statements (i) and (iii) of Lemma 3 if we choose the constant term c^G appropriately.

Let p_{-i}^ω denote the probability of the opponent's block history $h_{-i}^{T_b}$ being regular given (ω, G) , conditional on that the state is ω and players play s^x with $x_{-i}^\omega = G$. Note that this probability does not depend on the choice of x as long as $x_{-i}^\omega = G$, so it is well defined. Then let

$$\begin{aligned} c^G &= (1 - p_{-i}^\omega)(\bar{v}_i^\omega + 2\bar{g}_i^\omega) \\ &\quad + E\left[\frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2 - b_i^\omega(h_{-i}^{T_b}) \mid \omega, s^x\right]. \end{aligned} \quad (17)$$

Again, the expected value of $|e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$ and $b_i^\omega(h_{-i}^{T_b})$ does not depend on the choice of x and, thus, c^G is well defined.

Given this constant term c^G , the resulting transfer rule $U_i^{\omega, G}$ satisfies Lemma 3(i). To see why, suppose that players play s^x with $x_{-i}^\omega = G$. It follows from (15) and (16) that if the transfer rule $\tilde{U}_i^{G, \omega}$ is used, player i 's expected payoff in the complete-information transfer game is

$$p_{-i}^\omega \bar{v}_i^\omega - (1 - p_{-i}^\omega) 2\bar{g}_i^\omega,$$

where p_{-i}^ω is the probability of the opponent's history being regular. Hence, if the modified transfer rule $U_i^{G, \omega}$ is used, player i 's payoff in the complete-information transfer game is

$$\begin{aligned} \frac{1 - \delta}{1 - \delta^{T_b}} G_i^\omega(s^x, U_i^{\omega, G}) &= p_{-i}^\omega \bar{v}_i^\omega - (1 - p_{-i}^\omega) 2\bar{g}_i^\omega + c^G \\ &\quad + E \left[b_i^\omega(h_{-i}^{T_b}) - \frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2 \middle| \omega, s^x \right]. \end{aligned}$$

Plugging (17) into this equation, we obtain statement (i) of Lemma 3.

Step 5: Proof of statement (iii) What remains is to prove Lemma 3(iii). That is, we need to show $-(\bar{v}_i^\omega - \underline{v}_i^\omega) < (1 - \delta)U_i^{\omega, G}(h_{-i}^{T_b}) < 0$ for all $h_{-i}^{T_b}$.

We begin by showing the first inequality, $-(\bar{v}_i^\omega - \underline{v}_i^\omega) < (1 - \delta)U_i^{\omega, G}(h_{-i}^{T_b})$. By the definition of $\bar{g}_i^\omega$, we have $\frac{1 - \delta}{1 - \delta^{T_b}} \sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) \leq \bar{g}_i^\omega$ regardless of the action sequence $(a^1, \dots, a^{T_b})$. Plugging this into (15) and (16), we obtain

$$\frac{\delta^{T_b}(1 - \delta)}{1 - \delta^{T_b}} \tilde{U}_i^{\omega, G}(h_{-i}^{T_b}) \geq -3\bar{g}_i^\omega$$

and, hence,

$$\frac{\delta^{T_b}(1 - \delta)}{1 - \delta^{T_b}} U_i^{\omega, G}(h_{-i}^{T_b}) \geq -3\bar{g}_i^\omega + c^G + b_i^\omega(h_{-i}^{T_b}) - \frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2$$

for each $h_{-i}^{T_b}$. Equivalently,

$$(1 - \delta)U_i^{\omega, G}(h_{-i}^{T_b}) \geq \frac{1 - \delta^{T_b}}{\delta^{T_b}} \left(-3\bar{g}_i^\omega + c^G + b_i^\omega(h_{-i}^{T_b}) - \frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2 \right).$$

For a fixed T , if we take δ close to 1, $\frac{1 - \delta^{T_b}}{\delta^{T_b}}$ becomes arbitrarily close to 0, so that the right-hand side is greater than $-(\bar{v}_i^\omega - \underline{v}_i^\omega)$. This implies the desired inequality, $-(\bar{v}_i^\omega - \underline{v}_i^\omega) < (1 - \delta)U_i^{\omega, G}(h_{-i}^{T_b})$.

Now we prove the remaining inequality, $(1 - \delta)U_i^{\omega, G}(h_{-i}^{T_b}) < 0$. We consider the following two cases.

Case 1: $h_{-i}^{T_b}$ is regular given (ω, G) . In this case, in all but one period of the main round, players play a^{ω, x^ω} with $x_{-i}^\omega = G$, which yields more than $\bar{v}_i^\omega + 2\varepsilon$ to player i , according to (3) and (4). So for sufficiently large T and δ close to 1, we have $\frac{1-\delta}{1-\delta^{T_b}} \sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) > \bar{v}_i^\omega + 2\varepsilon$. Plugging this into (15) yields

$$\frac{(1-\delta)\delta^{T_b}}{1-\delta^{T_b}} \tilde{U}_i^{\omega, G}(h_{-i}^{T_b}) < -2\varepsilon.$$

Hence,

$$\begin{aligned} \frac{(1-\delta)\delta^{T_b}}{1-\delta^{T_b}} U_i^{\omega, G}(h_{-i}^{T_b}) &< -2\varepsilon + c^G + b_i^\omega(h_{-i}^{T_b}) - \frac{\varepsilon}{T} \sum_{t \in T(i)} |e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2 \\ &\leq -2\varepsilon + c^G + b_i^\omega(h_{-i}^{T_b}). \end{aligned}$$

Note that

$$c^G \leq (1 - p_{-i}^\omega)(\bar{v}_i^\omega + 2\bar{g}_i^\omega) + \sqrt{2}\varepsilon - E[b_i^\omega(h_{-i}^{T_b})|\omega, s^x],$$

since $|e(z_{-i}^t) - C_i^\omega(a^*)e(\hat{z}_i^t)|^2 \leq \sqrt{2}$. Plugging this into the above inequality, we have

$$\begin{aligned} \frac{(1-\delta)\delta^{T_b}}{1-\delta^{T_b}} U_i^{\omega, G}(h_{-i}^{T_b}) \\ < -(2 - \sqrt{2})\varepsilon + (1 - p_{-i}^\omega)(\bar{v}_i^\omega + 2\bar{g}_i^\omega) - E[b_i^\omega(h_{-i}^{T_b})|\omega, s^x] + b_i^\omega(h_{-i}^{T_b}). \end{aligned}$$

Note that when T is large, p_{-i}^ω approximates 1 and $b_i^\omega(h_{-i}^{T_b})$ approximates 0 for all $h_{-i}^{T_b}$. (This follows from Lemma 9.) Hence, for sufficiently large T ,

$$\frac{(1-\delta)\delta^{T_b}}{1-\delta^{T_b}} U_i^{\omega, G}(h_{-i}^{T_b}) < -(2 - \sqrt{2})\varepsilon < 0$$

as desired.

Case 2: $h_{-i}^{T_b}$ is irregular given (ω, G) . The proof is very similar to that for Case 1 and, hence, is omitted.

A.3 Proof of Lemma 4

Fix i and ω arbitrarily. In what follows, we construct a transfer rule $U_i^{\omega, B}$ that satisfies statements (i)–(iii) in Lemma 4.

We begin by introducing the notion of *regular histories*. The definition here is slightly different from that in the proof of Lemma 3. The opponent's history is regular if she does not deviate from the prescribed strategy $s_{-i}^{x_{-i}}$ and she makes the correct inference $\omega(-i) = \omega$. Formally, the opponent's block history $h_{-i}^{T_b}$ is *regular given (ω, B)* if it satisfies all the following conditions.

(B1) Player $-i$ chooses a_{-i}^* in the learning round.

(B2) Player $-i$ reports $\omega(-i) = \omega$.

(B3) Player $-i$ reports $x_{-i}^\omega = B$ in the first period of the main round.

(B4) Player $-i$ followed the prescribed strategy $s_{-i}^{x_{-i}}$ in the second or later periods of the main round.

A history $h_{-i}^{T_b}$ is *irregular given* (ω, B) if it is not regular.

Step 1: Construction of $U_i^{\omega, B}$ Let $c^B > 0$ be a constant that is specified later. Then choose a transfer rule $U_i^{\omega, B} : H_{-i}^{T_b} \rightarrow \mathbf{R}$ so that we have the following scenarios.

- For each history $h_{-i}^{T_b} = (a^t, z_{-i}^t)_{t=1}^{T_b}$ that is regular given (ω, B) , choose $U_i^{\omega, B}(h_{-i}^{T_b})$ so that it solves

$$\frac{1-\delta}{1-\delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) + \delta^{T_b} U_i^{\omega, B}(h_{-i}^{T_b}) \right] = \underline{v}_i^\omega - \frac{\tau \varepsilon}{T} - c^B, \quad (18)$$

where τ is the number of periods such that player i deviated from a^* during the opponent's learning round.

- For each irregular $h_{-i}^{T_b}$, choose $U_i^{\omega, B}(h_{-i}^{T_b})$ so that

$$\frac{1-\delta}{1-\delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) + \delta^{T_b} U_i^{\omega, B}(h_{-i}^{T_b}) \right] = 2\bar{g}_i^\omega - \frac{\tau \varepsilon}{T} - c^B. \quad (19)$$

In words, if the opponent plays the prescribed strategy and reports the correct inference $\omega(-i) = \omega$ (so that the history $h_{-i}^{T_b}$ is regular), we adjust the transfer $U_i^{\omega, B}(h_{-i}^{T_b})$ in such a way that player i 's total payoff in the complete-information transfer game is $\underline{v}_i^\omega - c^B$. As will be explained, c^B is a constant number close to 0, so this payoff is approximately the target payoff $\underline{v}_i^\omega$. By contrast, if the opponent deviates or reports something else, we give a huge positive transfer to player i and her total payoff goes up to $2\bar{g}_i^\omega - c^B$. If player i deviates in the opponent's learning round, it decreases the transfer a bit, due to the term $\frac{\tau \varepsilon}{T}$.

Step 2: Proof of statement (ii) We claim that the transfer rule above satisfies statement (ii) of Lemma 4. That is, we show that the prescribed strategies s_i^{GG} , s_i^{GB} , s_i^{BG} , and s_i^{BB} are all best replies in the complete-information transfer game with $(\omega, U_i^{\omega, B})$ if the opponent's current plan is x_{-i} with $x_{-i}^\omega = B$. The result follows from the next two lemmas.

LEMMA 12. *Player i is indifferent over all actions in player i 's learning round, the summary report round, the main round, and the detailed report round, regardless of the past history. Hence, deviating from $s_i^{x_i}$ during these rounds is not profitable.*

PROOF. By the construction of $U_i^{\omega, B}$, player i 's payoff in the complete-information transfer game depends only on whether the opponent's block history $h_{-i}^{T_b}$ is regular and on the number of periods such that player i deviated from a^* during the opponent's learning round. The result follows because player i 's play cannot influence whether the resulting history is regular. $\square$

LEMMA 13. When T is large enough, a_i^* is the unique best reply in each period of the opponent's learning round, regardless of the past history. Hence, deviating from $s_i^{x_i}$ during the opponent's learning round is not profitable.

PROOF. During the opponent's learning round, deviating from a_i^* has two effects. First, it affects the distribution of the opponent's inference $\omega(-i)$ and, hence, the probability of the opponent's history being regular. Second, it decreases the transfer $U_i^{\omega,B}$ due to the term $\frac{\tau\varepsilon}{T}$. From Lemma 1(ii) and the law of large numbers (more precisely, Hoeffding's inequality), the first effect is at most of order $O(\exp(-T^{\frac{1}{2}}))$. By contrast, the second effect is proportional to $\frac{1}{T}$. Thus for large T , the second effect dominates, so that playing a_i^* is optimal. This shows that statement (ii) of Lemma 4 holds. $\square$

Step 3: Proof of statement (i) Now we choose the constant term c^B in such a way that the resulting transfer rule $U_i^{\omega,B}$ satisfies statement (i) of Lemma 4.

Let p_{-i}^ω denote the probability of the opponent making the correct inference $\omega(-i) = \omega$, given that the true state is ω and players play a^* in the learning round. Then let

$$c^B = (1 - p_{-i}^\omega)(2\bar{g}_i^\omega - \underline{v}_i^\omega) > 0. \quad (20)$$

Given this constant term c^B , the resulting transfer rule $U_i^{\omega,B}$ satisfies statement (i) of Lemma 4. To see why, suppose that players play s^x with $x_{-i} = B$. It follows from (18) and (19) that player i 's expected payoff in the complete-information transfer game is

$$\frac{1 - \delta}{1 - \delta^{T_b}} G_i^\omega(s^x, U_i^{\omega,B}) = p_{-i}^\omega(\underline{v}_i^\omega - c^B) + (1 - p_{-i}^\omega)(2\bar{g}_i^\omega - c^B),$$

where p_{-i}^ω is the probability of the opponent's history being regular. Plugging (20) into this equation, we obtain statement (i) of Lemma 4.

Step 4: Proof of statement (iii) To complete the proof of Lemma 4, we need to show that the constructed transfer rule $U_i^{\omega,B}$ satisfies statement (iii) of Lemma 4.

We first show that $(1 - \delta)U_i^{\omega,B}(h_{-i}^{T_b}) < \bar{v}_i^\omega - \underline{v}_i^\omega$ for each $h_{-i}^{T_b}$. By the definition of $\bar{g}_i^\omega$, player i 's average payoff in the block, $\frac{1 - \delta}{1 - \delta^{T_b}} [\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t)]$, is at least $-\bar{g}_i^\omega$. Then from (18), (19), and $c^B > 0$, we have $\frac{\delta^{T_b}(1 - \delta)}{1 - \delta^{T_b}} U_i^{\omega,B}(h_{-i}^{T_b}) < 3\bar{g}_i^\omega$; equivalently, $(1 - \delta)U_i^{\omega,B}(h_{-i}^{T_b}) < \frac{(1 - \delta^{T_b})3\bar{g}_i^\omega}{\delta^{T_b}}$. For a fixed T , by taking sufficiently large δ , the right-hand side becomes arbitrarily small. Hence, we have $(1 - \delta)U_i^{\omega,B}(h_{-i}^{T_b}) < \bar{v}_i^\omega - \underline{v}_i^\omega$.

Next we show that $U_i^{\omega,B}(h_{-i}^{T_b}) > 0$ for each $h_{-i}^{T_b}$. We consider the following two cases.

Case 1: $h_{-i}^{T_b}$ is regular given (ω, B) . In this case, in most periods of the main round, players played the action profile a^{ω,x^ω} with $x_{-i} = B$ or the opponent played the minimax action $\alpha_{-i}^\omega(i)$. Both these actions yield payoffs lower than $\underline{v}_i^\omega - \varepsilon$ to player i , according to (1) and (2). Hence, when T is sufficiently large and δ is close to 1, we have

$$\frac{1 - \delta}{1 - \delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) \right] < \underline{v}_i^\omega - \varepsilon.$$

Then since $c^B \rightarrow 0$ as $T \rightarrow \infty$ (this follows from the fact that [Lemma 1](#) ensures $p_{-i}^\omega \rightarrow 1$), we obtain

$$\frac{1-\delta}{1-\delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) \right] < \underline{v}_i^\omega - \varepsilon - c^B.$$

Plugging this into (18), we obtain $U_i^{\omega,B}(h_{-i}^{T_b}) > 0$.

Case 2: $h_{-i}^{T_b}$ is irregular given (ω, B) . Since the value $\bar{g}_i^\omega$ is greater than player i 's stage-game payoff for any action profile a , we have

$$\frac{1-\delta}{1-\delta^{T_b}} \left[\sum_{t=1}^{T_b} \delta^{t-1} g_i^\omega(a^t) \right] < 2\bar{g}_i^\omega - \varepsilon - c^B.$$

Plugging this into (19), we obtain $U_i^{\omega,B}(h_{-i}^{T_b}) > 0$.

REFERENCES

- Basu, Pathikrit, Kalyan Chatterjee, Tetsuya Hoshino, and Omer Tamuz (2018), “Repeated coordination with private learning.” Unpublished paper, [arXiv:1809.00051](#). [1180]
- Bhaskar, Venkataraman and Ichiro Obara (2002), “Belief-based equilibria in the repeated prisoners’ dilemma with private monitoring.” *Journal of Economic Theory*, 102, 40–69. [1180]
- Chen, Bo (2010), “A belief-based approach to the repeated prisoners’ dilemma with asymmetric private monitoring.” *Journal of Economic Theory*, 145, 402–420. [1180]
- Cr  mer, Jacques and Richard P. McLean (1988), “Full extraction of the surplus in Bayesian and dominant strategy auctions.” *Econometrica*, 56, 1247–1257. [1178]
- Cripps, Martin, Jeffrey Ely, George Mailath, and Larry Samuelson (2013), “Common learning with intertemporal dependence.” *International Journal of Game Theory*, 42, 55–98. [1180]
- Cripps, Martin, Jeffrey C. Ely, George J. Mailath, and Larry Samuelson (2008), “Common learning.” *Econometrica*, 76, 909–933. [1176, 1180, 1186]
- Dekel, Eddie, Drew Fudenberg, and David K. Levine (2004), “Learning to play Bayesian games.” *Games and Economic Behavior*, 46, 282–303. [1181]
- Ely, Jeffrey C., Johannes H  rner, and Wojciech Olszewski (2005), “Belief-free equilibria in repeated games.” *Econometrica*, 73, 377–415. [1179, 1198]
- Ely, Jeffrey C. and Juuso V  lim  ki (2002), “A robust folk theorem for the prisoner’s dilemma.” *Journal of Economic Theory*, 102, 84–105. [1180]
- Fong, Kyna, Olivier Gossner, Johannes H  rner, and Yuliy Sannikov (2011), “Efficiency in a repeated prisoners dilemma with imperfect private monitoring.” Working Paper No. 3434, Stanford Graduate School of Business. [1180, 1192]

- Fudenberg, Drew and David K. Levine (1991), "An approximate folk theorem with imperfect private information." *Journal of Economic Theory*, 54, 26–47. [1180]
- Fudenberg, Drew and David K. Levine (1994), "Efficiency and observability in games with long-run and short-run players." *Journal of Economic Theory*, 62, 103–135. [1196]
- Fudenberg, Drew, David K. Levine, and Eric Maskin (1994), "The folk theorem with imperfect public information." *Econometrica*, 62, 997–1039. [1179]
- Fudenberg, Drew and Yuichi Yamamoto (2010), "Repeated games where the payoffs and monitoring structure are unknown." *Econometrica*, 78, 1673–1710. [1176, 1180, 1181]
- Fudenberg, Drew and Yuichi Yamamoto (2011), "Learning from private information in noisy repeated games." *Journal of Economic Theory*, 146, 1733–1769. [1176, 1181]
- Hörner, Johannes and Stefano Lovo (2009), "Belief-free equilibria in games with incomplete information." *Econometrica*, 77, 453–487. [1176]
- Hörner, Johannes, Stefano Lovo, and Tristan Tomala (2011), "Belief-free equilibria in games with incomplete information: Characterization and existence." *Journal of Economic Theory*, 146, 1770–1795. [1176]
- Hörner, Johannes and Wojciech Olszewski (2006), "The folk theorem for games with private almost-perfect monitoring." *Econometrica*, 74, 1499–1544. [1177, 1180, 1186, 1187, 1190, 1198]
- Hörner, Johannes and Wojciech Olszewski (2009), "How robust is the folk theorem?" *Quarterly Journal of Economics*, 124, 1773–1814. [1180]
- Kandori, Michihiro (2002), "Introduction to repeated games with private monitoring." *Journal of Economic Theory*, 102, 1–15. [1180]
- Kandori, Michihiro (2011), "Weakly belief-free equilibria in repeated games with private monitoring." *Econometrica*, 79, 877–892. [1180]
- Kandori, Michihiro and Hitoshi Matsushima (1998), "Private observation, communication and collusion." *Econometrica*, 66, 627–652. [1211]
- Koren, Gilad (1992), "Two-person repeated games where players know their own payoffs." Unpublished paper, Courant Institute of Mathematical Sciences. [1176]
- Lehrer, Ehud (1990), "Nash equilibria of n-player repeated games with semi-standard information." *International Journal of Game Theory*, 19, 191–217. [1180]
- Mailath, George J. and Stephen Morris (2002), "Repeated games with almost-public monitoring." *Journal of Economic Theory*, 102, 189–228. [1180]
- Mailath, George J. and Stephen Morris (2006), "Coordination failure in repeated games with almost-public monitoring." *Theoretical Economics*, 1, 311–340. [1180]
- Mailath, George J. and Wojciech Olszewski (2011), "Folk theorems with bounded recall and (almost) perfect monitoring." *Games and Economic Behavior*, 71, 174–192. [1180]

- Mailath, George J. and Larry Samuelson (2006), *Repeated Games and Reputations: Long-Run Relationships*. Oxford University Press, New York, New York. [1180]
- Matsushima, Hitoshi (2004), “Repeated games with private monitoring: Two players.” *Econometrica*, 72, 823–852. [1180]
- Miller, David A. (2012), “Robust collusion with private information.” *Review of Economic Studies*, 79, 778–811. [1176]
- Piccione, Michele (2002), “The repeated prisoner’s dilemma with imperfect private monitoring.” *Journal of Economic Theory*, 102, 70–83. [1180]
- Sekiguchi, Tadashi (1997), “Efficiency in repeated prisoner’s dilemma with private monitoring.” *Journal of Economic Theory*, 76, 345–361. [1180]
- Shalev, Jonathan (1994), “Nonzero-sum two-person repeated games with incomplete information and known-own payoffs.” *Games and Economic Behavior*, 7, 246–259. [1176]
- Sugaya, Takuo (2012), “Belief-free review-strategy equilibrium without conditional independence.” Unpublished paper, Stanford Graduate School of Business. [1180]
- Sugaya, Takuo (2019), “Folk theorem in repeated games with private monitoring.” Unpublished paper, Stanford Graduate School of Business. [1176, 1180, 1192]
- Sugaya, Takuo and Yuochi Yamamoto (2019), *Common Learning and Cooperation in Repeated Games*. Working Paper No. 3781, Stanford Graduate School of Business. [1177, 1180, 1185]
- Wiseman, Thomas (2005), “A partial folk theorem for games with unknown payoff distributions.” *Econometrica*, 73, 629–645. [1181]
- Wiseman, Thomas (2012), “A partial folk theorem for games with private learning.” *Theoretical Economics*, 7, 217–239. [1177, 1181, 1185]
- Yamamoto, Yuichi (2007), “Efficiency results in N player games with imperfect private monitoring.” *Journal of Economic Theory*, 135, 382–413. [1180]
- Yamamoto, Yuichi (2009), “A limit characterization of belief-free equilibrium payoffs in repeated games.” *Journal of Economic Theory*, 144, 802–824. [1180]
- Yamamoto, Yuichi (2012), “Characterizing belief-free review-strategy equilibrium payoffs under conditional independence.” *Journal of Economic Theory*, 147, 1998–2027. [1180]
- Yamamoto, Yuichi (2014), “Individual learning and cooperation in noisy repeated games.” *Review of Economic Studies*, 81, 473–500. [1176, 1181, 1184]

Co-editor Simon Board handled this manuscript.

Manuscript received 18 June, 2019; final version accepted 1 January, 2020; available online 24 January, 2020.