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Advice from Multiple Experts: A Comparison of Simultaneous, Sequential, and Hierarchical Communication*

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Abstract

In this paper, I analyze an example in which two perfectly informed experts advise a decision maker. Each expert has private information about her own bias. I show that consulting two experts is better than consulting just one. I compare the efficiency of information transmission between simultaneous, sequential, and hierarchical forms of communication. I show that simultaneous communication achieves the highest efficiency, followed by sequential and hierarchical communication. However, hierarchical communication, in which a second expert chooses whether to block the first expert's message, achieves a moderate level of efficiency, even though the decision maker receives only one message. Finally, there are preference settings in which both sequential and hierarchical communication are superior to simultaneous communication.

KEYWORDS: expert opinions, strategic information transmission, multiple experts

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1 INTRODUCTION

Decision makers such as politicians, CEOs, and investors often rely on experts such as advisors, managers, and analysts, respectively, for advice. However, experts often have biases, as a result of conflicts of interest or matters of ideology. A common method that is believed to have the potential to alleviate the problem is to seek second opinions, which conceivably enables the decision makers to acquire a more complete understanding of the issues.

However, new difficulties arise when there are multiple experts, and hence multiple reports. Strategic interactions between experts become more complex– they may strengthen, rebut, and fine-tune each other's reports. It takes the decision maker extra time and energy to digest all the reports and to extract useful information from them. Furthermore, the decision maker is often an outsider to the experts' profession or group, and therefore is not informed about the preferences of the experts. Thus, it is important to find the kind of communication mechanisms with which the decision maker can achieve information transmission efficiency.

In this paper, I build a model of communication where two perfectly informed experts advise a single decision maker, based on the model of Crawford and Sobel (1982), with the feature that experts have private information about their own preferences. Using a symmetric example, I compare the decision maker's expected payoff under different communication mechanisms. In keeping with the convention applied in the literature, the reported opinions of experts are referred to as "messages."

The decision maker has the option to ask just one expert or to ignore the message from one of the experts. When he chooses to take advantage of both experts, he has various options.[1] The first option is to consult experts *simultaneously*, where neither expert observes the message sent by the other. The second option is to consult them *sequentially*, where the second expert observes the first expert's message before sending her own. I refer to these two mechanisms as *direct* communication mechanisms since the decision maker hears both experts' messages. In addition, I consider another option referred to as *hierarchical communication*, where one of the experts acts as a reviewer of the other expert's message and decides whether or not to pass it on. If she accepts the expert's message, then the decision maker hears the original message. If she rejects it, however, the decision maker receives a random message drawn from the distribution that is endogenously generated by interactions between the reviewer and the expert, which is to be elaborated upon later.

[1] For ease of discussion, I refer to the decision maker as "he," and each expert "she."

Note that, when using the hierarchical communication mechanism, the decision maker only receives one final message, as opposed to receiving two messages when using the direct communication mechanisms. In a sense, he delegates part of the task of information solicitation to the reviewer. This mechanism may be preferred by a decision maker who favours a simple mechanism. The hierarchical communication mechanism is of interest as it captures some of the features of many communication and organization structures in reality. For example, in corporations, lower-level employees make reports to the mid-level management, and what the higher-level executives receive is a selective pool of reports that are filtered by mid-level management.

I focus on symmetric equilibrium outcomes in these mechanisms and compare their communication efficiency. Consulting two experts is better than consulting just one. In the main example I consider, simultaneous communication fares the best among the two-expert mechanisms. Sequential communication allows for equilibria that are better than with hierarchical communication, but it also allows equilibria that are worse. In hierarchical communication, the reviewer serves as deterrence and safeguard against distortions by the biased expert. If rejection is carried out in equilibrium, however, then its performance is inferior relative to the direct consultation mechanisms.

However, the welfare comparisons may vary with the magnitude of the experts' biases. In particular, there exist values of the biases for which both sequential communication and hierarchical communication perform better than simultaneous communication.

The rest of the paper is organized as follows. Section 2 introduces the communication mechanisms and the equilibrium concept. Section 3 characterizes the most informative equilibria of the mechanisms. Section 4 compares welfare under the three different mechanisms. Section 5 discusses the results and the relationship that this paper has with the literature. Proofs are found in the appendix unless otherwise noted.

2 The Model

Two experts advise a decision maker, who takes an action from the set $Y = [-1, 1]$. The decision maker wants his action to match an underlying state, randomly drawn from the set $S = \{-1, 0, 1\}$, according to the uniform distribution. The decision maker does not know the state, but the experts do. In addition, each expert's bias is her private information. There are three possible types of experts that can be drawn from the set $X = \{-1, 0, 1\}$, each with probability $1/3$. The state and both experts' biases are independent of one another. Both the experts and the decision maker have quadratic-loss utility functions:

$$u(y,s,\tilde{b}) = -[y-(s+\tilde{b})]^2, \tag{1}$$

where y is the action taken by the decision maker, s is the true state, and $\tilde{b}$ is the bias of the agent. For the decision maker $\tilde{b}=0$, and for an expert of type $x \in X$, $\tilde{b}=b_x$, where

$$b_x = bx.$$

The following assumption restricts the range of values for b.

Assumption 1. The bias value b lies in $[17/21, 6/7]$.

This assumption ensures the validity of equilibrium construction for hierarchical communication in Section 3. The results may vary when b takes other values. First, there exists a fully revealing equilibrium for all communication mechanisms above when $b \leq 1/2$. The comparisons between different mechanisms may change when b is outside the range of values stated in Assumption 1. Section 4 conducts a further discussion of this point. Finally, the limitation to three messages below affects the equilibrium outcomes when b is relatively small, as without this limit there could exist equilibria where more than three messages are sent.

Each expert is allowed to send a message from a message space M. For the sake of tractability, I limit M to be $S=\{-1,0,1\}$.[2] The decision maker asks for advice from experts. He may choose to ask just one expert. If the decision maker asks both experts, he may choose among various mechanisms. In this paper, I consider the following three mechanisms: simultaneous communication, sequential communication, and hierarchical communication.

With the *simultaneous communication* mechanism, the decision maker chooses his action after hearing simultaneous messages from the two experts. Each expert is allowed to send a message from the message space M. In order to ensure clarity of notation, I label the experts A and B. Expert i's message is denoted as m^i, $i=A,B$. I define the strategy of expert i of type x as $m^i_x : S \to M$, for $i=A,B$ and $x \in X$. In other words, $m^i_x(s)$ is what expert i of type x would send if the state is $s \in S$. The

[2] This is *not* without loss of generality. There are scenarios in which allowing additional messages may improve communication between the experts and the decision maker. However, even in richer environments than that in this model, experts are sometimes limited to relatively small message spaces due either to conventions or to the decision maker's information processing constraints. For example, stock analysts overwhelmingly adopt the categorized ranking system, presumably to make their recommendations easier to comprehend for investors. Since the restriction applies to all mechanisms, I put all the mechanisms on a "level playing field." Notably, Austen-Smith (1993) and Morris (2001) also consider models with discrete spaces and restrict the message space to be the same as the state space.

decision maker's strategy is defined as $y : M \times M \to [-1,1]$, where $y(m^A, m^B)$ is the action taken by the decision maker when he receives the message pair (m^A, m^B).

With the *sequential communication* mechanism, expert A sends a message, expert B observes it and sends another message, and finally the decision maker hears *both* messages and chooses his action. With a slight abuse of notation (since m_x^B has already been used above as a function with a single argument), their strategies can be defined respectively as $m_x^A : S \to M$, and $m_x^B : S \times M \to M$. For A, $m_x^A(s)$ is the message sent by an expert of type x when the true state is s; for B, $m_x^B(s,t)$ is the message sent by an expert of type x when the true state is s and expert A has reported t. The decision maker's strategy is $y : M \times M \to [-1,1]$, where $y(m^A, m^B)$ represents the action taken when the message pair is (m^A, m^B).

With the *hierarchical communication* mechanism, expert A sends a message about the underlying state, but her message must pass through a reviewer (expert B) before reaching the decision maker. The reviewer may either reject the message or accept it. When she rejects it, the decision maker receives a random message coming from the endogenous distribution of messages generated by interactions between the experts. Without knowing whether the message he receives is an original message or a random one following a rejection, the decision maker takes his action based solely upon the message.

The random distribution of messages can be interpreted as being generated by a population of decision makers and experts facing identical uncertain situations. Furthermore, this mechanism is somewhat similar in spirit to mechanisms involving "veto power" in the cheap-talk literature.[3] The results in these models typically depend on the exogenously determined status quo when the decision maker vetoes the expert's recommendation. Here, in the hierarchical communication mechanism, the random distribution can be viewed as an endogenously generated status quo.

Let $\Gamma = (\gamma_{-1}, \gamma_0, \gamma_1)$ be the random distribution of messages eventually received by the decision maker, where γ_m is the probability of message $m \in M$. Let the expert's strategy be $m_x : S \to M$, where $m_x(s)$ is the message sent by an expert of type $x \in X$ when the state is s. In addition, let $\tilde{m}_x(s,t) = 1\{m_x(s) = t\}$. Let the reviewer's strategy be $r_v : S \times M \to \{0,1\}$, where $r_v(s,t) = 1$ indicates that a reviewer of type v rejects message t when the state is s and $r_v(s,t) = 0$ indicates that she accepts the message. The decision maker's strategy is defined as $y : M \to [-1,1]$. For the sake of convenience, I use y_m to refer to the action taken by the decision maker after hearing message $m \in M$.

[3]See Gilligan and Krehbiel (1987), Krishna and Morgan (2001a), Dessein (2002), Mylovanov (2008), and Board and Dragu (2006).

EQUILIBRIUM

For the sake of tractability, I consider only pure strategy equilibria.[4] I adopt the solution concept of perfect Bayesian equilibrium. For the direct communication mechanisms, this means that each expert sends a message that maximizes her expected utility and the decision maker chooses the optimal action given his Bayesian beliefs. For the hierarchical communication mechanism, this additionally requires that the reviewer's decision of rejection or acceptance is optimal and that the distribution of messages resulting from play is the same as the distribution where the random message is drawn when there is a rejection. The last requirement can be written

$$\begin{aligned}\gamma_t &= \textstyle\sum_{s\in S} P_s \sum_{x\in X} P_x \tilde{m}_x(s,t) \sum_{v\in X} P_v [1 - r_v(s,t)] \\ &\quad + \textstyle\sum_{s\in S} P_s \sum_{x\in X} P_x \sum_{t'\in M} \tilde{m}_x(s,t') \sum_{v\in X} P_v r_v(s,t') \cdot \gamma_t,\end{aligned}$$

where P_s, P_x, and P_v stand for the probabilities of state s, type x expert, and type v reviewer occurring respectively. They are all equal to $1/3$ in this model.

As in all cheap-talk models, two issues arise. The first is the meaning of messages. I make the following assumption to reduce essentially identical equilibria into one. The idea is that a high message is more likely to indicate a higher state than a low message. A right-biased expert is more likely to send a right-biased message than other types of experts. An expert is more likely to report a state to be high when it is indeed high. This assumption does not pose additional restrictions for simultaneous communication and hierarchical communication. However, it does for sequential communication, although I am not aware of any non-monotonic equilibrium informationally superior to monotonic ones.[5]

Assumption 2. (*Monotonicity*.) The decision maker's strategy must be nondecreasing in the message(s) he receives. The experts' messages must be nondecreasing in the state and their biases.

The second issue that arises is multiplicity of equilibria. In particular, a babbling equilibrium always exists. Following previous work in which the cheap-talk model is applied, I will focus on the most informative among all symmetric equilibria.[6]

[4] This is without loss of generality for a single expert and expert B in the sequential mechanism, as b is less than one, which precludes mixing by any expert. However, equilibria in mixed strategies my exist for other mechanisms.

[5] Notably, there also exist "partisan bickering equilibria" in which monotonicity is violated and in which the decision maker does even worse than in the single-expert case. See Li (2008) for details.

[6] Chen, Kartik, and Sobel (2008) provide an equilibrium selection criterion that justifies the focus on the most informative equilibrium in Crawford and Sobel's model with complete information

Definition 1. A pure strategy profile $(\hat{m},(\hat{r}),\hat{y})$ is a *mirror image* of another strategy profile $(m,(r),y)$ if for all $i=A,B$, $x,v\in X$, $s,t\in S$, and $m\in S$ or $S\times S$, the following conditions are satisfied where they apply:

(SE1) simultaneous communication: $m^i_x(s)=-\hat{m}^i_{-x}(-s)$;
sequential communication: $m^A_x(s)=-\hat{m}^A_{-x}(-s)$;
hierarchical communication or consulting one expert: $m_x(s)=-\hat{m}_{-x}(-s)$.
(SE2) sequential communication: $m^B_x(s,t)=-\hat{m}^B_{-x}(-s,-t)$;
hierarchical communication: $r_v(s,t)=\hat{r}_{-v}(-s,-t)$.
(SE3) $\hat{y}(m)=-y(-m)$.
(SE4) hierarchical communication: $\gamma_t=\hat{\gamma}_{-t}$ for all $t\in M$.

Definition 2. An equilibrium is *symmetric* if and only if the equilibrium strategy profile is a mirror image of itself.

Intuitively, in a symmetric equilibrium experts and reviewers of type 1 and -1 behave in a similar way, and state values -1 and 1 and messages -1 and 1 are treated in a similar way. Consequently, when I characterize symmetric equilibria, I need only consider the behaviour of experts (and reviewers) of types 0 and 1.

Before characterizing the equilibria, note that full revelation is not possible in equilibrium. This is made clear in the next section. Here, I offer only an informal argument for the hierarchical communication mechanism, in place of a formal proof. Due to the quadratic loss utility function, no reviewer would reject the message 0, because it would generate a random message symmetrically distributed over -1, 0, and 1. Thus, a right-biased expert would prefer to report -1 as 0, ruling out full revelation as an equilibrium outcome.

3 Equilibrium

In this section, I characterize the most informative equilibrium for each mechanism.

about the expert's bias, although it remains unclear how their result can be generalized to models with uncertainty about biases.

CONSULTING ONE EXPERT

Proposition 1. *When the decision maker consults only one expert, the only symmetric equilibrium is as follows:*
1) $m_0^*(s) = s$, $m_1^*(s) = s+1$ *if* $s \neq 1$, *and* $m_1^*(1) = 1$*;*
2) $y_m^* = (2/3)m$.
In equilibrium, the decision maker's expected payoff is $-10/27$.

In equilibrium, biased experts misrepresent the state whenever possible. That is, an expert of type 1 reports state -1 as 0 and 0 as 1. They are able to do this as there are no forces to counteract or punish biased messages. In a sense, this is the worst that could occur to the decision maker in an informative equilibrium. Now, I turn to the investigation of whether the introduction of another expert improves the situation.

SIMULTANEOUS COMMUNICATION

In this mechanism, each expert simultaneously sends a message to the decision maker. In addition to the symmetry conditions above, another symmetry condition is added.

Assumption 3. (*Anonymity.*) $m_x^A(s) = m_x^B(s)$ for all $x \in X$ and $s \in S$.

The idea behind this condition is that an expert's messages are not affected by her labelling, but only by the underlying state and her bias. As a result, in equilibrium, the decision maker's action is based only on the combination of message pairs, but not on the source of messages. The main result is as follows.

Proposition 2. *In the simultaneous communication game, strategy profile (A), as defined in Table 1, is the only pure strategy symmetric equilibrium that satisfies anonymity. In this equilibrium, the decision maker's expected payoff is* $-94/405$.

Strategy profile (A) is a "replication" of the equilibrium of the one-expert case. Here, biased messages are sometimes balanced by the other expert who may have a different bias. For example, although a right-biased expert still reports state -1 as 0, her report is offset by the other expert when the other expert's bias is -1 or 0, which occurs with a probability of $2/3$; the decision maker then takes the action $-2/3$ after receiving the message pair $(0,-1)$ or $(-1,0)$. On the other hand, in the one-expert mechanism, he takes action 0 when he receives the message 0, which is farther away from his most preferred action -1 in state -1. Therefore, compared

Table 1: Strategy Profile (A)

m^A, m^B	Type 0	Type 1
State -1	-1	0
State 0	0	1
State 1	1	1

y	$m_B = 0$	$m_B = 1$
$m_A = -1$	$-2/3$	0
$m_A = 0$	0	$2/3$
$m_A = 1$	$2/3$	$4/5$

Table 2: Strategy Profile (C)

m^A	Type 0	Type 1
State -1	-1	0
State 0	0	1
State 1	1	1

m_0^B	$m^A = -1$	$m^A = 0$	$m^A = 1$
State -1	-1	-1	-1
State 0	1	0	-1
State 1	1	1	1

m_1^B	$m^A = -1$	$m^A = 0$	$m^A = 1$
State -1	1	0	-1
State 0	1	1	1
State 1	1	1	1

y	$m_B = 0$	$m_B = 1$
$m_A = -1$	$-4/5$	$-1/2$
$m_A = 0$	0	$2/3$
$m_A = 1$	$4/5$	$4/5$

to the case with one expert, the improvement in information transmission is due to the fact that with two experts, the decision maker has a higher chance of getting undistorted information from one of the experts.

SEQUENTIAL COMMUNICATION

In the sequential communication mechanism, the second expert sends a message based on what the first expert has reported. The main result can be desccribed as follows.

Proposition 3. *Strategy profiles (C), as defined in Table 2, is the most informative monotonic symmetric equilibria of the sequential communication game. The decision maker's expected payoff is* $-104/405$.

In equilibrium, expert A always distorts her message towards the direction of her bias, just as she would in the one-expert mechanism. For example, an expert of type 1 reports -1 as 0 and 0 as 1. Expert B behaves as if she were the first expert and distorts her message towards her bias, if expert A has not sent a biased message. If expert A has done so, then if expert B has the same bias as expert A, she may further distort it, make a moderate report, or correct the distortion by expert A it proves to be excessive (for example, reporting -1 as 1). If she is unbiased or if her bias is the opposite of expert A's, then she always chooses to offset the distortion by expert A, if this option is available in equilibrium. For example, an expert B of type 0 would like to report 1 if expert A has reported state 0 as -1. Compared with the one-expert mechanism, the improvement in information transmission is due to the fact that the second expert has a chance to offset the distortion introduced by the first expert.

Hierarchical communication

In the hierarchical communication mechanism, the reviewer decides whether to reject the expert's message in favour of a random one, or to pass the message on. Formally, when the message of an expert is rejected by a reviewer, the reviewer will draw a message from the endogenous symmetric distribution, $(\gamma, 1-2\gamma, \gamma)$, where $\gamma \in (0, 1/2)$.

Proposition 4. *For the hierarchical communication mechanism, strategy profile (E), as defined in Table 3, is the only symmetric equilibrium of the game (*$y_1^* = 46/63$ *and* $\gamma = 7/23$*). The decision maker's expected payoff is* $-194/567$.

In the above equilibrium, the expert follows what she would do in the one-expert mechanism. But, if she is biased, her distortion in state 0 is rejected by a reviewer with the opposite bias or with no bias. Rejection occurs only in cases where an unbiased reviewer would also like to reject the message. Since the unbiased reviewer has the same preferences as the decision maker, such rejection improves the payoff of the decision maker. However, the threat of rejection is not sufficient to deter the biased expert from distorting the state.

4 Comparisons

In this section, I discuss the welfare comparisons between the communication mechanisms considered above and their robustness to different setups.

Table 3: Strategy Profile (E)

m^A	Type 0	Type 1
State -1	-1	0
State 0	0	1
State 1	1	1

r_0	$m=-1$	$m=0$	$m=1$
State -1	0	0	1
State 0	1	0	1
State 1	1	0	0

r_1	$m=-1$	$m=0$	$m=1$
State -1	0	0	1
State 0	1	0	0
State 1	1	0	0

Results of the comparisons

Table 4 offers a summary both in terms of absolute payoffs and the improvements from the babbling outcome relative to simultaneous communication. Since von Neumann-Morgenstern expected utility is unique up to affine transformations, the second column accurately reflects the welfare comparisons between different equilibria. The first observation is that all two-expert mechanisms do better than the one-expert mechanism, thus conforming to the idea that second opinions improve information transmission. The second observation is regarding the ranking of information efficiency for the two-expert communication mechanisms. Considering the most informative equilibrium, the ranking is (from the highest to the lowest): 1. simultaneous communication; 2. sequential communication; 3. hierarchical communication. However, there exist equilibria in sequential communication in which the decision maker is worse off than he is under hierarchical communication. This is the case in strategy profile (D) in Table 5, in which the decision maker's payoff is $-16/45$, or 71.6 in the percentage terms of Table 4.

The three mechanisms differ in terms of the way in which the second expert enhances communication. With simultaneous communication, neither expert can respond to the other's specific messages–the two experts send independent messages and the decision maker aggregates them and forms an assessment. With two experts, there is a higher likelihood that the decision maker will receive undistorted information from one of the experts. In contrast, with sequential communication, the second expert's message can be tailored to offset or to strengthen the first expert's biased message. This is a mixed blessing–though it causes the most efficient equilibrium in sequential communication to be close to that in simultaneous communication, it also allows equilibria that are not very informative. For example, in

Table 4: Comparisons of decision maker's payoff in equilibria–the second column is an affine normalization of payoffs such that babbling becomes 0 and simultaneous communication becomes 100.

	Absolute	Percentage
Babbling	$-2/3$	0
One Expert	$-10/27$	68.2
Hierarchical	$-194/567$	74.7
Sequential	$-104/405$	94.3
Simultaneous	$-94/405$	100

Table 5: Strategy Profile (D)

m^A	Type 0	Type 1
State -1	-1	0
State 0	0	1
State 1	1	1

m_0^B	$m^A = -1$	$m^A = 0$	$m^A = 1$
State -1	-1	-1	-1
State 0	1	0	-1
State 1	1	1	1

m_1^B	$m^A = -1$	$m^A = 0$	$m^A = 1$
State -1	1	0	-1
State 0	1	0^*	1
State 1	1	0^*	1

y	$m_B = 0$	$m_B = 1$
$m_A = -1$	$-4/5$	$-1/2$
$m_A = 0$	0	0
$m_A = 1$	$4/5$	$4/5$

strategy profile (D), once the first expert sends the message 0, the second expert has no possibility to change the decision maker's inference.[7] With hierarchical communication, communication is enhanced through yet another channel. If the reviewer rejects a message, a random message is generated, causing all three actions, one of which least liked by the expert, to occur with a significant probability. Therefore, the expert may be deterred from sending a biased message by the threat of rejection. The actual act of rejection when the expert does send a biased message also reduces the amount of harm inflicted by the biased message. However, if in equilibrium the threat of rejection is carried out with a positive probability, it results in a loss in the decision maker's payoff, which explains the inferior performance of hierarchical communication relative to the direct communication mechanisms.

In this paper, I model hierarchical communication as a mechanism where interactions between experts are not made transparent to the decision make and only

[7] See also Li (2008).

the final message is observable to him. This corresponds to economic situations in which the decision maker just receives one unified recommendation, instead of hearing each expert's opinion and what they think about each other's opinion. For example, a political leader would only choose one economic policy proposal, without necessarily knowing how the proposal has been promoted to prominence.

ROBUSTNESS

In the preceding discussion, I have focused on values of the bias that satisfy Assumption 1. Equilibrium characterization, as well as comparisons of information transmission efficiency, may vary when the value of the bias changes. In particular, when $b = 2/3$, the comparison between the most informative equilibrium in each communication mechanism is different from that of Table 4. Here, the ranking of information transmission efficiency of the three mechanisms becomes (from the highest to the lowest): 1. sequential communication; 2. hierarchical communication; 3. simultaneous communication.[8] The unique equilibrium for simultaneous communication is the same as before. However, as demonstrated by the equilibrium in Table 7, in sequential communication, the smaller magnitude of bias affords the second expert a better opportunity to fine-tune the first expert's biased report. For example, in state 0, if the first expert has a positive bias and sends message 1, the second expert would send message 0 instead of 1 when she also has positive bias. Thus, the message pair $(1,1)$ is only sent in state 1. This reduction in the distortion results in an increase in the decision maker's payoff. In hierarchical communication, as demonstrated in Table 8, there now exists an equilibrium in which rejection deters the biased expert from distorting the state 0. This implies that no rejection actually takes place in equilibrium, hence no loss of payoffs from such a rejection. This is the reason why hierarchical communication performs relatively well.

In hierarchical communication, after the rejection of the expert's message, a message is drawn from a random distribution. Randomness is a punishment for an expert who sends a biased message because it results in the expert's least preferred action being taken with a positive probability. Such randomness is essential to the mechanism. If, after rejection, the decision maker receives no message at all, then he would always take action 0, which is not an effective deterrence. However, one may let the distribution of the random message be exogenously given, similar to Blume, Board, and Kawamura (2007), who assume that if the expert's message fails to reach the decision maker, the decision maker receives a "noise" message randomly drawn from a uniform distribution. This alternative setup would

[8] Similar to the case $b \in [17/21, 6/7]$, there also exist informative equilibria in sequential communication that are worse than simultaneous and hierarchical communication.

Table 6: Comparisons of decision maker's payoff in equilibria for $b = 2/3$– the second column is an affine normalization of payoffs such that babbling becomes 0 and sequential communication becomes 100.

	Absolute	Percentage
Babbling	$-2/3$	0
One Expert	$-10/27$	60
Simultaneous	$-94/405$	88
Hierarchical	$-2/9$	90
Sequential	$-14/81$	100

Table 7: Most informative equilibrium in sequential communication when $b = 2/3$

m^A	Type 0	Type 1
State -1	-1	0
State 0	0	1
State 1	1	1

m_0^B	$m^A = -1$	$m^A = 0$	$m^A = 1$
State -1	-1	-1	-1
State 0	1	0	-1
State 1	1	1	1

m_1^B	$m^A = -1$	$m^A = 0$	$m^A = 1$
State -1	0	0	-1
State 0	1	1	0^*
State 1	1	1	1

y	$m_B = 0$	$m_B = 1$
$m_A = -1$	$-2/3$	0
$m_A = 0$	0	$2/3$
$m_A = 1$	$2/3$	1

slightly alter the incentives of the expert and the reviewer, but it would not affect the qualitative results.

5 Discussion and Related Literature

In this paper, I have analyzed an example of communication in which there are two experts and a single decision maker. The experts have perfect knowledge of the state of the world. In addition, they have private information about their own biases. I have compared information transmission efficiency between three mechanisms: simultaneous, sequential, and hierarchical communication.

In related work, Austen-Smith (1993) studies communication between two experts and a decision maker in the context of legislation rules, comparing sequential communication with simultaneous communication. In his model, the state and message spaces are binary, and experts are imperfectly informed. He finds that

Table 8: Equilibrium in hierarchical communication when $b = 2/3$

m^A	Type 0	Type 1
State -1	-1	0
State 0	0	0^*
State 1	1	1

r_0	$m = -1$	$m = 0$	$m = 1$
State -1	0	0	1
State 0	1	0	1
State 1	1	0	0

r_1	$m = -1$	$m = 0$	$m = 1$
State -1	0	0	1
State 0	1	0	0
State 1	1	0	0

sequential communication is superior to simultaneous communication. Also in a model with a binary state space, Ottaviani and Sørensen (2001) show that simultaneous communication is superior to sequential communication when the prior over the two states is symmetric, while the opposite may be true when it is not. In contrast, Krishna and Morgan (2001a,b) show that in the "uniform-quadratic case," simultaneous communication allows for the full revelation of information, when information about experts' biases is common knowledge (Battaglini (2002) also offers a nice discussion of this result). A similar construction would also work in my model under common knowledge of biases. Furthermore, Krishna and Morgan (2001b) show that full revelation of information is *not* possible when using sequential communication if both experts are biased, which would also be true in my model under common knowledge of biases. Therefore, my welfare comparison results in the case of uncertain biases provide mixed support for the superiority of simultaneous communication. On the one hand, simultaneous communication is the best for relatively large bias values; on the other hand, sequential and hierarchical communication are both better than simultaneous communication for some relatively small bias values.

Applying the cheap-talk model, Gilligan and Krehbiel (1989) and Krishna and Morgan (2001a) compare the efficiency of the legislation process under the "closed rule" and the "open rule," when the legislature consults two perfectly informed committees on one piece of legislation.[9] Krishna and Morgan (2001a) show that the open rule can achieve full information revelation while the closed

[9]The open rule is the same as simultaneous communication in my model, while under the closed rule the second committee can only influence the legislature's choice between the first committee's proposal and the status quo.

rule cannot.[10] Hori (2006) compares horizontal communication, sequential communication, and delegation in their efficiency at decision making, when each expert observes a separate piece of information.

The main distinction between my paper and the ones described above is that I allow biases of the experts to be unknown to the decision maker. Cheap-talk with uncertainty about a single expert's bias has been analyzed by Dimitrakas and Sarafidis (2005), Li and Madarasz (2008), Morgan and Stocken (2003), Morris (2001), and Ottaviani (2000).

The "hierarchical communication" mechanism I analyze in this model, where the reviewer decides what the decision maker receives from the expert, is related to the literature on mediated cheap talk, e.g., papers by Ganguly and Ray (2005), Ivanov (2009), Mitusch and Strausz (2005), and Goltsman, Horner, Pavlov, and Squintani (2009). However, the reviewer is equally as informed as the expert, whereas the mediator is uninformed. In addition, the reviewer's strategies have to be incentive compatible, whereas the mediator is disinterested, with the exception of Ivanov's model, where the mediator is also potentially biased.

6 APPENDIX: PROOFS

In the following proofs, the reader is sometimes referred to the supplement to the paper, which can be found at http://alcor.concordia.ca/~mingli/research/combsub_supp1.pdf, and is available from the author.

Proof of Proposition 1. Since we consider symmetric equilibria, $y_{-1} = -y_1$ and $y_0 = 0$. Let $y = y_1$ to save notation. In informative equilibria, $y > 0$. Since y_s and s have the same sign, we have $-(y_s - s)^2 < -(y_{s'} - s)^2$ for all $s, s' \in S, s \neq s'$. Therefore, $m_0^*(s) = s$ for all $s \in S$.
Now, consider $m_1^*(s)$. Note that $b_1 = b \in [17/21, 6/7]$.
First, it is straightforward to see $m_1^*(1) = 1$. Second, $m_1^*(0) = 1$, as $u(1,0,b) = -(y-(0+b))^2 > -(0-(0+b))^2 > -(-y-(0+b))^2$ for all $b > 1/2$ and $y \in (0,1]$. Finally, $m_1^*(-1) \neq 1$ because $b < 1$ implies $|0-(-1+b)| < |y-(-1+b)|$. If $m_1^*(-1) = -1$ (by symmetry, $m_{-1}^*(1) = 1$), then $y = 3/4$. Since $b \geq 17/21 > 5/8$, $|0-(-1+b)| = 1-b < b-1/4 = |-y-(-1+b)|$, which makes $m_1(-1) = -1$ not optimal. If $m_1^*(-1) = 0$, $y = 2/3$, thus $|0-(-1+b)| = 1-b < b-1/3 = |-y-(-1+b)|$ as $b \geq 17/21 > 2/3$. Hence, $m_1^*(-1) = 0$ is optimal.

[10] However, their equilibrium construction has been criticized as relying on arguably implausible out-of-equilibrium beliefs (Krehbiel, 2001, Battaglini, 2002).

Table 9: Messages, probabilities, and decisions for simultaneous communication

(m^A, m^B)	$\text{Prob}(m^A, m^B, s = -1+0+1)$	$y(m^A, m^B)$
$(1,1)$	$0+\frac{1}{3}\times\frac{1}{3}\times\frac{1}{3}+\frac{1}{3}\times\frac{2}{3}\times\frac{2}{3}$	$\frac{4}{5}$
$(1,0)$ or $(0,1)$	$0+\frac{1}{3}\times\frac{1}{3}\times\frac{1}{3}+\frac{1}{3}\times\frac{2}{3}\times\frac{1}{3}$	$\frac{2}{3}$
$(1,-1)$	$0+\frac{1}{3}\times\frac{1}{3}\times\frac{1}{3}+0$	0
$(0,0)$	$\frac{1}{3}\times\frac{1}{3}\times\frac{1}{3}+\frac{1}{3}\times\frac{1}{3}\times\frac{1}{3}+\frac{1}{3}\times\frac{1}{3}\times\frac{1}{3}$	0

Thus, the strategy profile specified in the proposition is the unique symmetric equilibrium. Furthermore, the decision maker's expected utility is $-10/27$, by straightforward calculation. □

Proof of Proposition 2. First, the following lemma describes the experts' strategies in equilibrium.

Lemma 1. *When the decision maker consults two experts simultaneously, in equilibrium, the following must be true about experts' strategies: for $i = A, B$, $m_0^i(s) = m_s^i(s) = s$ for $s = -1$ and 1, and $m_0^i(0) = 0$.*

The proof of it can be found in the supplement. Intuitively, unbiased experts never try to distort information. A biased expert tells the truth about the state when the state is at the extreme in the direction of her bias, as by so doing she induces her favourite action.

In what follows I only show that Strategy Profile (A) *is* an equilibrium. For the proof of uniqueness, please see the supplement to the paper.

Table 9 lists probabilities and decisions for each message pair.[11] Clearly, $m_1^A(0) = 1$ is optimal. I need also check the optimality of $m_1^A(-1) = 0$. I omit the calculation here, but as long as $b > 58/105$, it turns out for $t = -1$ and 1
$\frac{1}{3}\sum_{x\in X} u(y(0, m_x^A(0)), -1, b_1) > \frac{1}{3}\sum_{x\in X} u(y(t, m_x^A(0)), -1, b_1)$,
which is certainly satisfied since $b \geq 17/21 > 58/105$. Thus $m_1^A(-1) = 0$ is optimal.

Straightforward calculation yields that the decision maker's expected payoff is $-94/405$. □

Proof of Proposition 3. I first establish a lemma that describes experts' equilibrium strategies, the proof of which can be found in the supplement to the paper.

Lemma 2. *When the decision maker consults two experts sequentially, the following must be true about experts' strategies in equilibrium:*

[11] The notation $\text{Prob}(m^A, m^B, s = -1+0+1)$ means that in that column, probabilities of (m^A, m^B, s) are separated by "+" according to different s.

1. $m_0^A(1) = m_1^A(1) = 1$ *and* $m_0^A(0) = 0$*;*
2. $m_0^B(1,m^A), m_1^B(1,m^A) \in \arg\max_{m^B} y(m^A, m^B)$*;*
3. $m_0^B(0,0) = 0$*,* $m_1^B(0,-1) \in \arg\max_{m^B} y(-1,m^B)$*, and* $m_1^B(0,0) \in \arg\max_{m^B} y(0,m^B)$.

Monotonicity requires that expert A reports 1 in state 1 if she is of type 1. If she does not, then monotonicity implies $m_x(s) = 0$ for all $x \in X$, which renders expert A's messages uninformative. Symmetry requires that the first expert reports 0 in state 0 when she is of type 0. When the true state is 1 and the expert is of type 1 or 0, the expert wants the decision maker to take the highest action. The other results in the lemma follow from similar lines of argument.

By Lemma 2, the only parts of expert A's strategy left to be determined are $m_1^A(-1)$ and $m_1^A(0)$. Note that in strategy profile (C), $m_1^A(-1) = 0$ and $m_1^A(0) = 1$. Here, I only verify that strategy profile (C) *is* an equilibrium. Please refer to the supplement of the paper for a characterization of other monotonic symmetric equilibria, which shows that (C) is the most informative among those.

Note that in strategy profile (C), $y(0,-1) < y(0,0)$. This immediately implies $m_1^B(0,0) = 1$, $m_1^B(1,0) = 1$, and $m_0^B(1,0) = 1$. We also know $m_1^B(-1,0) \neq 1$ since $y(0,0)$ is better than $y(0,1)$ in state -1 for an expert of type 1. Since $y(0,1) \geq 2/3$, we conclude that $m_1^B(-1,0) = 0$ as a type 1 expert's most preferred action in state -1 is $-1+b > -1/3$, which is closer to $y(0,0) = 0$ than to $y(0,-1)$. This gives us $y(0,1) = 2/3$.

If $y(1,1) = y(1,0)$, it is possible that $(1,1)$ or $(1,0)$ (but not both) is never sent, but it does not matter to our discussion since we may replace them with each other without essentially changing the strategy profile. Now we have $y(1,1) > 2/3 > y(1,-1)$, which implies $m_{-1}^B(1,1) = -1$ and $m_{-1}^B(0,1) = m_0^B(0,1) = -1$ as $b \geq 2/3$. Hence $y(1,-1) \leq 1/2$, which implies $m_1^B(0,1) \neq -1$ since $b \geq 17/21 > 3/4$ and $y(1,1) \leq 1$. Thus, $y(1,1) = y(1,0) = 4/5$ and $y(1,-1) = 1/2$. The case $y(1,0) = y(1,-1)$ is similar, which results in $y(1,1) = 4/5$ and $y(1,0) = y(1,-1) = 1/2$.

Now, I check the optimality of $m_1^A(-1) = 0$ and $m_1^A(0) = 1$. First, note that $m_1^A(-1) = 0$ induces actions $y(0,-1) = -2/3$ with probability $2/3$ and $y(0,0)$ with probability $1/3$, that $m_1^A(-1) = -1$ induces actions $y(-1,-1) = -4/5$ with probability $2/3$ and $y(-1,1) = -1/2$ with probability $1/3$, and that $m_1^A(-1) = 1$ induces action $y(1,-1) = 1/2$ for sure. Thus, $m_1^A(-1) = 0$ is better than $m_1^A(-1) = -1$ since a type 1 expert prefers $-2/3$ to $-4/5$ and 0 to $-1/2$ in state -1, due to our assumption $b \in [17/21, 6/7]$. The difference in expected utility between $m_1^A(-1) = 0$ and $m_1^A(-1) = 1$ is

$$-\frac{1}{3}[2(-\frac{2}{3}-(-1+b))^2+(0-(-1+b))^2]-(\frac{1}{2}-(-1+b))^2 = \frac{199}{36}-\frac{17}{3}b,$$

which is positive given Assmption 1. Thus, $m_1^A(-1) = 0$ is optimal. Second, $m_1^A(0) = 1$ induces actions $y(1,1) = 4/5$ with probability $1/3$ and $y(1,-1) = 1/2$ with probability $2/3$, while $m_1^A(0) = 0$ induces actions $y(0,1) = 2/3$, $y(0,0) = 0$, and $y(0,-1) = -2/3$ with equal probabilities. Thus, $m_1^A(0) = 1$ is a better response than $m_1^A(0) = 0$ since a type 1 expert prefers $4/5$ to $2/3$ and $1/2$ to any nonpositive action, due to our assumption $b \in [17/21, 6/7]$. We conclude that the strategy profile constitutes an equilibrium. Note that it is **strategy profile (C)**, where it is straightforward to show the decision maker's expected payoff is $-104/405$. □

Proof of Proposition 4. First, I establish two lemmas regarding the reviewer and the expert's equilibrium strategies.

If a reviewer of a certain type rejects a message in some state, then intuitively, an expert of the same type should never send that message in the same state, as there must exist an alternative message that she strictly prefers. The following lemma establishes this fact.

Lemma 3. *In equilibrium, if $r_v^*(s,t) = 1$, then $\tilde{m}_v^*(s,t) = 0$, i.e., $m_v^*(s) \neq t$.*

Proof. In equilibrium, a reviewer of type $v \in X$ rejects message $t \in M$ in state $s \in S$ if and only if

$$\sum_{t'} -\gamma_{t'} \left[y_{t'}^* - (s + b_v)\right]^2 > -\left[y_t^* - (s + b_v)\right]^2. \tag{2}$$

Since $r_v^*(s,t) = 1$, Equation (2) must hold. This implies that $-[y_t^* - (s + b_v)]^2 = u(y_t^*, s, b_v) < \max_{t' \in S} u(y_{t'}^*, s, b_v)$. Let $\tilde{t} = \arg\max_{t' \in S} u(y_{t'}^*, s, b_v)$. Then if an expert of type v sends the message $\tilde{t}$ in state s, her expected payoff is at least $\sum_{t'} \gamma_{t'} u(y_{t'}^*, s, b_v)$, which is greater than $u(y_t^*, s, b_v)$ by Equation (2). Since the expert's expected payoff from sending message t is a convex combination of this expression and $u(y_t^*, s, b_v)$, the expert is strictly better off sending message $\tilde{t}$. Hence $\tilde{m}_v^*(s,t) = 0$. □

Note that symmetry is not needed in the above proof. So, Lemma 3 applies to all equilibria of the game, not just symmetric ones. Now, I establish that the only possible behaviour of the reviewer in symmetric equilibria is that in $(E2)$, which also implies certain behaviour of the expert.

Lemma 4. *In a symmetric equilibrium,*

1. *$r_0^*(s,t) = 1$ if $(s,t) = (-1,1), (0,-1), (0,1)$ or $(1,-1)$, and 0 otherwise; $r_1^*(s,t) = 1$ if $(s,t) = (-1,1), (0,-1)$ or $(1,-1)$, and 0 otherwise;*
2. *$m_0(s) = s$ for all $s \in S$ and $m_1(1) = 1$.*

The proof of the above lemma can be found in the supplement to the paper. Intuitively, rejection occurs only if the reviewer prefers the resulting random message drawn from the endogenous symmetric distribution to the original message. Because of the quadratic loss utility function, no reviewer prefers the random message to the message 0 and rejects the message 0. At the same time, a reviewer of type 0 rejects messages 1 and -1 in state 0 and message 1 in state -1, since these messages are the worst for her to pass on to the decision maker. For similar reasons, a reviewer of type 1 rejects the message -1 when the state is 0 or 1. These arguments do not depend on the size of the bias (as long as $b > 1/2$, which precludes a fully revealing equilibrium). However, the argument for type 1 not rejecting -1 in state -1 and rejecting 1 in state -1 does depend on the fact that her bias is not very large.

Now we resume the proof of Propsition 4. By Lemmas 3 and 4, $m_1(-1) \neq 1$ and $m_1(0) \neq -1$. What is left to be determined is whether $m_1(0) = 0$ or 1 and whether $m_1(-1) = -1$ or 0. Observe that since when the decision maker receives no messages, a message is randomly drawn from the endogenously generated distribution $(\gamma, 1-2\gamma, \gamma)$, the following must be true:

$$\begin{aligned}
\gamma &= P(s=1)[P(x=0,1)+P(x=1)(1-\tilde{m}_1(-1,0))] \\
&\quad +P(s=0)P(x=1)\tilde{m}_1(0,1)[P(v=1)+P(v=-1,0)\gamma] \\
&\quad +P(s=0)P(x=-1)\tilde{m}_{-1}(0,-1)P(v=0,1)\gamma \\
&= \left(\frac{1}{3}-\frac{\tilde{m}_1(-1,0)}{9}\right)+\frac{\tilde{m}_1(0,1)}{9}\left(1-\frac{2}{3}(1-2\gamma)\right),
\end{aligned}$$

where I have used the fact $\tilde{m}_{-1}(0,-1) = \tilde{m}_1(0,1)$ by symmetry. From the above equation, I obtain

$$\gamma = \frac{1}{9}\left(1-\frac{2}{3}(1-2\gamma)\right)\tilde{m}_1(0,1) - \frac{\tilde{m}_1(-1,0)}{9} + \frac{1}{3}, \tag{3}$$

$$y_1 = \frac{P(s=1,m=1)}{P(m=1)} = \frac{1}{\gamma}\left[\frac{1}{3}-\frac{\tilde{m}_1(-1,0)}{9}\right]. \tag{4}$$

Given the reviewer's strategies, an expert of type 1 should choose according to the following comparisons.

(i) Since neither 0 nor -1 is ever rejected in state -1, $m_1(-1) = 0$ if and only if

$$y_1 \geq 2(1-b).$$

(ii) Since in state 0, 0 is not rejected and 1 is rejected by types 0 and -1, $m_1(0) = 0$ is optimal if and only if

$$-b^2 + [(1-\frac{2}{3})(y_1-b)^2 + \frac{2}{3}(2\gamma {y_1}^2 + b^2)] \geq 0 \quad \Leftrightarrow \quad y_1 \geq \frac{2b(1-\frac{2}{3})}{1-\frac{2}{3}(1-2\gamma)}$$

(iii) Using (2), $r_1(-1,-1) = 0$ is optimal if and only if

$$y_1 \leq \frac{2(1-b)}{1-2\gamma}.$$

As fully revealing equilibria do not exist, we consider only three cases: (a) $m_1(-1) = 0$ and $m_1(0) = 0$; (b) $m_1(-1) = 0$ and $m_1(0) = 1$; (c) $m_1(-1) = -1$ and $m_1(0) = 1$.

(a) It can also be represented as $\tilde{m}_1(-1,0) = 1$ and $\tilde{m}_1(0,1) = 0$.
By (3), we have $\gamma = 2/9$, and by (4), we have $y_1 = (1/3-1/9)/(2/9) = 1$.
According to condition (iii) in this proof, we need $1 \leq 2(1-b)/(5/9)$. This requires $b \leq 13/18$, which is violated given Assumption 1 ($b \in [17/21, 6/7]$).

(b) This case can be represented by $\tilde{m}_1(-1,0) = 1$ and $\tilde{m}_1(0,1) = 1$.
By (3), we have $\gamma = 7/23$, and by (4), we have $y_1 = \frac{2}{9}/\gamma$.
According to condition (i) in this proof, we need $y_1 \geq 2(1-b)$, which translates into $(1-b-2/9)(1-2/3) \leq 1-2(1-b)-2/9$. This holds since $b \geq 2(1-b)$ given Assumption 1.
Using $1-2/3\cdot(1-2\gamma) = 9(\gamma-2/9)$, condition (ii) becomes $9y_1(\gamma-2/9) \leq 2b\cdot(1-2/3)$, which, as $\gamma y = 2/9$, becomes

$$b(1-\frac{2}{3})^2 + (2b-\frac{5}{9})(1-\frac{2}{3}) - \frac{4}{9} \geq 0,$$

which simplifies into $b \geq \frac{17}{21}$. By Assumption 1, condition (ii) is satisfied.
Now we check condition (iii). We need $2/9\cdot(1-2\gamma)/\gamma \leq 2(1-b)$, which simplifies into

$$1-\frac{2}{3} \geq \frac{1}{3(1-b)} - 2.$$

This inequality holds when $b \leq 6/7$, which is satisfied by Assumption 1. So we conclude that **strategy profile (E)** is an equilibrium.

(c) This case can be represented by $\tilde{m}_1(-1,0) = 0$ and $\tilde{m}_1(0,1) = 1$.
By(3), we have $\gamma = 10/23$, and by (4), we have $y_1 = \frac{1}{3}/\gamma$.
By condition (i) of this proof, we need $y_1 \leq 2(1-b)$, which requires $1/3\cdot(7/9+2/9\cdot(1-2/3)) \leq (1-b)(2/3+2/9\cdot(1-2/3))$, an impossible statement since $1-b < 1/3$. So this is not an equilibrium strategy profile.

The proposition follows from the above arguments. □

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