COSTLY COMMUNICATION IN GROUPS: THEORY AND AN EXPERIMENT

ALISTAIR J. WILSON

ABSTRACT. I develop a novel model of group-based communication in which group members communicate with one another. Communication is costly in the sense that group members who choose to send or listen to messages incur costs. Equilibrium strategies have an intuitive characterization—those with the best information send, those with the worst information receive. Free-riding leads to less information exchange than is optimal, but a simple system of transfers and subsidies can correct this. Examining the model's predictions with an experiment I find that subjects over-communicate when costs are high, but fail to benefit from this as much as they should. Additionally, I find that listening costs are more harmful to welfare, in contrast with the theory which indicates sending costs.

Keywords: Group Communication, Information transmission, Information public goods

People provide information to one another: Teams meet to exchange expertise on joint projects. Boards convene to obtain consensus on the best strategy for their firms. Friends and colleagues share movie and restaurant recommendations. Anonymous internet users provide feedback on products they purchased, and New Yorkers sometimes take the time to give directions to tourists. In each case, information is provided freely, even where the individuals proffering and receiving the information incur costs, for example, their time, effort or attentiveness. So there must be some benefit to the social exchange of information that can offset these costs.

This preference for others' accurate choices might be the result of structural factors aligning interests (the joint project or common employer), or the product of a repeated game, where cooperation with others is driven by the stick of exclusion or the carrot of reciprocity (colleagues sharing information). It might be driven by explicit social preferences, where information providers derive pleasure from helping others (anonymous product raters, strangers giving directions). Regardless of the motive, when the provision of information is

---

Date: February, 2014.
Address: Department of Economics, University of Pittsburgh, 230 South Bouquet St., Pittsburgh, PA 15260. *Email*: alistair@pitt.edu.
I would like to thank the following for their feedback in the design and implementation of this paper: Mariagiovanna Baccara, John Duffy, Matthew Embrey, Alessandro Lizzeri, Daniel Martin, Debraj Ray, Ariel Rubinstein, Matan Tsur, Andy Schotter, Ennio Stacchetti, Emanuel Vespa, Lise Vesterlund and Leeat Yariv. I am especially grateful to Guillaume Fréchette for his patience and advice. My thanks to the Center for Experimental Social Science at New York University for funding.

costly, no information will be provided unless senders have incentives to incur costs. However, even in situations where individuals are aligned in their interests over information transfer we encounter a classic public-goods-type problem: individuals in the group transfer and acquire less information than an efficient planner would. Costs are fully internalized, while the positive effects from information transfer (on both sides of the exchange) are only partially felt.

This paper constructs a model of information exchange within a group facing a common-value choice (product A or product B), where the group members have aligned incentives to truthfully communicate private information to one another. Each agent makes two decisions: whether to send information to others and whether to listen to others, where each activity incurs a known cost. After the communication phase ends, individuals make their product choices. The model therefore endogenizes the provision and acquisition of information under fixed transmission frictions, predicting who will provide and/or acquire information, with a simple equilibrium characterization. This equilibrium outcome is shown to be inefficient, but where efficiency might be attainable using subsidies.

The model is then directly implemented in a series of laboratory experiments, which manipulate the costs for sending and acquiring information, to try and understand how behavior matches with the equilibrium predictions, and the scope for intervention. In addition, the laboratory experiment provides some insight into whether previously documented instances of over-communication might extend to common-interest environments.

My results indicate broad agreement with the first-order comparative statics—as costs for providing or acquiring information increase, subjects participate in these activities less—and the model successfully ranks the benefits derived. In terms of levels, my experimental findings indicate that when costs for either communication activity are high, that subjects over-communicate relative to the equilibrium. In this common-interest environment, over-communication has the possibility to produce welfare gains, however, the laboratory findings indicate subjects do worse than the second-best equilibrium level. An updating bias that puts too much weight on private information relative to the information acquired from others leads to sub-optimal choices. Though subjects do not make great use of the information they acquire, each side continues to provide and consume information at a high rate. As such, the communication costs incurred through information exchange end up dominating the (potentially much larger) benefits from over-communication.

In policy terms, where the theory indicates large welfare gains from subsidizing those providing information, my experiment indicates more muted gains. In terms of improving information aggregation, subsidizing acquisition produces the strongest effect on final choices. However, the opportunity costs of this type of subsidy are not readily covered by benefits from improved outcomes. In fact, the experimental results indicate that the *presence* of costly communication channel with strong frictions can lead to behavior that reduces welfare. When the costs for provision and acquisition are both high, the average subject does worse than the individually rational point, not communicating at all. This finding bolsters the somewhat counter-intuitive arguments that we can (behaviorally at least) increase our productivity by removing our ability to communicate—for example, by withdrawing from online social networks or having email-free days.

In terms of organization, the next subsection surveys the relevant theoretical and experimental literatures. I then outline the theoretical model in section 2, before deriving some key results on the characterization of equilibrium and efficiency. I then illustrate the model through the experimental parametrization in section 3, providing some key comparative statics that the experiment will subsequently examine. The results from the experiment are documented in section 4, where I compare the observed behavior (communication decisions, updating rules) and welfare to the theoretic predictions. Finally, I summarize the results and discuss the contribution in the conclusion.

1.1. **Literature.** The literature on communication highlights three motivations for communication: information transmission; coordination; and persuasion and analogy.[1,2] I focus purely on the first, the transmission of private payoff-relevant information between agents.

The starting point for much of the literature on information transmission is Crawford and Sobel (1982). With an elegantly simple model, the paper demonstrates that misaligned preferences between sender and receiver lead to an impossibility for full revelation with cheap talk—the sender and receiver can not commit to revealing all the information and splitting the potential surplus in a Pareto-improving manner.[3]

Within a group setting, the theoretical literature has examined how preference conflicts and communication interact. Banerjee and Somanathan (2001) examine a leader who aggregates information about group members' preferences, and makes a final choice for the group, influenced by their own position and that of the group. As preferences diverge, type misreporting leads to information aggregation failures. Osborne, Rosenthal, and Turner (2000) examine a voting situation where costly participation (attending a meeting) determines a policy outcome. Similar to my own setting, fixed costs leads heterogeneous agents to sort themselves

[1]This distinction is made quite clearly and references are given in Austen-Smith and Feddersen (2005).

[2]For experimental work examining costly communication for coordination see Blume, Kriss, and Weber (2012a,b) and references therein.

[3]Costly misreporting—that is, a desire to truthfully report via a cost for dishonesty—is considered as an equilibrium refinement in Chen, Kartik, and Sobel (2008); Kartik (2009); Chen (2011). Similarly, Olszewski (2004) discusses environments where a preference for honesty on the part of the sender and a partially informed receiver can lead to full revelation.

into differing actions, here attending the meeting or not (in my model providing and/or acquiring). Where their setting leads to partisans from each side attending the meeting, my own leads to those with conflicting information providing it to the group. In my setting the agents are aligned ex post, so the number of partisans works to inform all sides, rather than just resolve conflict.

The closest theory paper to my own is Dewatripont and Tirole (2005). They similarly model communication as a bilaterally costly process with aligned incentives for information exchange. In their model each side chooses a degree of investment in the communication medium. The sender can invest in making their information easier to understand (writing a better paper), and the listener can invest in trying to parse the provided information (re-reading the paper multiple times).[4] Similar to my setting, equilibrium tensions lead to underinvestment by both sides of the exchange, as costs are fully internalized and benefits are not. However, in my group setting, additional tensions emerge through free-riding, as information provision is substitutable between group-members. A closely related paper with this free-riding tension is Smorodinsky and Tennenholtz (2006). They examine an environment where group members choose to acquire costly private information before a group vote. Individuals under-invest in information acquisition, as they will likely not be pivotal in the final vote when others acquire. In my model the acquisition tensions are different: the benefit to acquiring information is through better personal choices rather than a collective outcome, and the quality of information is endogenous, depending on others' provision.

The literature on information aggregation has a large body of work focused on voting, where aggregation occurs through a fixed mechanism, with each participant's input a vote. My model has some connections to common-value costly voting models.[5] Costly messages are similar to costly votes, as each is made with the intention of changing a final outcome, from incorrect to correct. However, rather than a fixed mechanism though which votes lead to outcomes, messages in my setting are inputs to group member's specific product choice. Pivotality remains an important concept, as senders of information only derive communication benefits from discrete changes to a listener's final choice. Like costly voting, this provides a retarding force on the amount of information provided, as individuals will only incur costs if they believe they can change the outcome. However, the final decisions in my environment are endogenous, determined by listener's preferences and posteriors, rather than a fixed collective-choice mechanism. Increased provision of information can increase the number

[4]See also Dessein and Santos (2006); Calvó-Armengol, de Martí, and Prat (2011) for models of endogenous communication with costs.

[5]For a review of much of the theory and some representative results see Taylor and Yildirim (2010).

of listener's who are swayed by messages, and subsequently information acquisition can increase.

In terms of the experimental literature, a body of work has focused on tensions between agents for information transmission: Crawford and Sobel environments.[6] The robust experimental finding is that subjects over-communicate, in the sense of overly truthful communication, with a large amount of heterogeneity in behavior. This over-communication has been explained as a failure in mutual best response (Gneezy, 2005; Cai and Wang, 2006; Wang, Spezio, and Camerer, 2010), where subjects best-respond to non-equilibrium conjectures about the other participants' play.[7] In contrast, in my environment participants have common interests, and all communication is honest. My experiment finds both under- and over-communication of information, depending on the cost structure. Where I find over-communication, it is in the quantity of messages not the quality. By removing ex-post conflicts between agents my experiments are better able to characterize communication behavior in efficiency terms.

The closest experiment to my own is McCubbins and Rodriguez (2006), where they examine group decisions with costs for both sending and listening. They find that deliberation is most effective when communication is completely free, or when the costs are only present for sending messages to others.[8] However, when costs are for listening to others there is a reduction in payoffs compared to a no-communication baseline. When there are costs for both sending and receiving they find outcomes that are significantly below the no-communication level, broadly consistent with my own results.[9] The advantage of the present work is a clear theoretical framework within which to examine and contrast the results: this allows us, for instance, to evaluate the welfare effects of various communication cost structures. Additionally my own experiment makes a greater use of experimental control, with subjects' private information and beliefs about others' information directly measured.

2. Theoretical Model

2.1. **Environment.** I examine a common-interest environment for a group of n agents, where their outcomes depend on a binary state of nature $\omega \in \Omega := \{A, B\}$. Each group

[6] See Dickhaut, McCabe, and Mukherji (1995), Gneezy (2005), Cai and Wang (2006), Wang, Spezio, and Camerer (2010). See also extensions to the standard model in Chung and Harbaugh (2012); Battaglini and Makarov (2011); Lai, Lim, and Wang (2011); Vespa and Wilson (2014)

[7] See Stahl and Wilson (1994, 1995); Nagel (1995); Crawford and Iriberri (2007) for further discussion and experimental evidence for level-k type models of behavior.

[8] For experiments comparing decision making in aligned groups with cheap unstructured communication between individuals see Blinder and Morgan (2005); Cooper and Kagel (2005).

[9] Additionally, they find a decreasing effect on utility as the group increases in size, which is potentially problematic given the group incentive comes through unanimity.

member $i \in \{1, \ldots, n\}$ can increases the group's payoff by matching their final choice y_i to the realized state. Though each group member is *ex ante* identical, they each receive private signals about the state, and the aim of the model is to examine how the presence of a costly communication channel can affect the groups final choice profile $y \in \Omega^n$. Group member's state-dependent payoffs will be given by

$$u_i(y,\omega) := \alpha \cdot \mathbf{1}\left\{y_i = \omega\right\} + (1-\alpha) \cdot \frac{1}{n-1} \sum_{j \neq 1}^{n} \mathbf{1}\left\{y_j = \omega\right\}, \tag{1}$$

where $\mathbf{1}\left\{\cdot\right\}$ is the indicator function, and $\alpha \in (0,1)$ is a preference parameter. Agents' payoffs are therefore modeled as a weighted function of their own choice and the average choice of the group. I will examine the behavior of group members across three stages: i) group members receive private signals and determine their interim beliefs, x_i; ii) each individual makes decisions on whether or not to provide information (send messages) and/or acquire information from others (listen to messages); and iii) after exchanging information, each makes their final choice y_i.

The model's starting point is therefore the private signals. I assume that each group member receives a private signal with probability q, and with probability $1-q$ they are uninformed. Given independent private signals, all that matters to final choice is aggregating the interim posteriors of each agent. Because Ω is binary, we can summarize the posterior of each agent by $x_i = \Pr\left\{\omega = A \,|\text{Signal}_i\right\}$. The model therefore abstracts from any particular signal process, and just uses a reduced-form, where each signal is an interim posterior on the event $\omega = A$. Each agent's signal is therefore an independent draw from a state dependent distribution F_ω over $X = [0,1]$.[10] I will assume the signal distributions satisfy the following assumptions:

Assumption 1 (Symmetry)**.** *For every* $x \in [0,1] \setminus \left\{\frac{1}{2}\right\}$, $F_A\left(x\right) = 1 - F_B\left(1-x\right)$.

Assumption 2 (Continuity)**.** $F_\omega(x)$ *has a density* $f_\omega(x)$ *everywhere on* $X \setminus \left\{\frac{1}{2}\right\}$.

The first assumption requires symmetry over the private information possible for each state: if the state is A and there is some probability a signal will lead me to be Z percent sure

[10] A *reduced-form signaling distribution* in this binary setting is therefore any state-conditioned pair of distributions (F_A, F_B) over $[0,1]$ such that a x_i satisfies the following restriction

$$x_i = \Pr\left\{\omega = A \,|x_i\right\}.$$

Given a density and the symmetry assumptions below this leads to the restriction that $f_A(1-x) = \frac{1-x}{x} \cdot f_A(x)$. So the reduced-form signal density is an arbitrary (up to scale) function on $(\frac{1}{2}, 1]$, with the density on $[0, \frac{1}{2})$ pinned down.

the state is A, then, conditional on the state being B there is the same probability a signal leads to being Z percent sure the state is B ($100 - Z$ percent sure on A). The assumption acts to pin down the distribution F_B given F_A, and is made for tractability.[11] Assumption 2 is technical, and allows me to focus on pure-strategy equilibria, and can be relaxed without much qualitatively changing. The assumptions explicitly allow for a mass-point at the interim-prior $\frac{1}{2}$, the uninformed type, which occurs with probability $1 - q$.

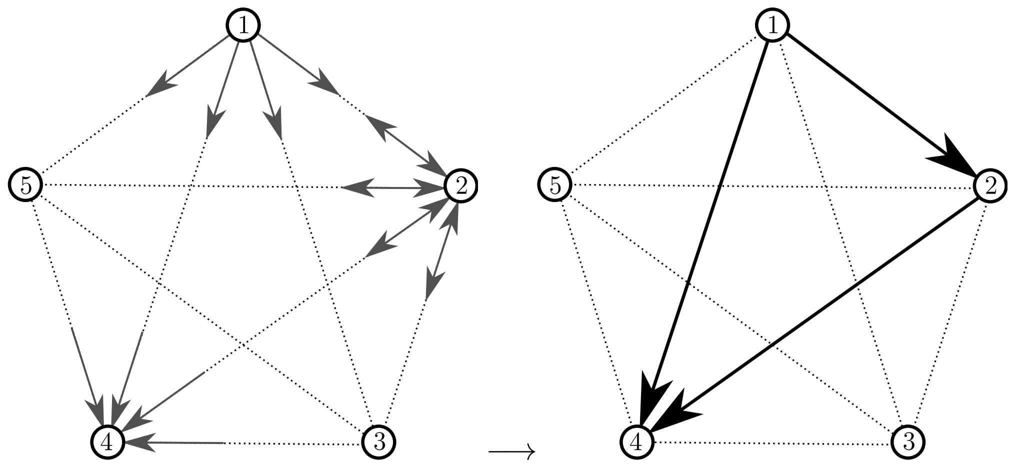
In the second stage of the model group members, given their private signals, make simultaneous communication decisions. I will limit the message-space to be coarse, $M = \{m_A, m_\emptyset, m_B\}$, though my equilibrium characterization holds with a richer message space.[12] The two meaningful messages in $\{m_A, m_B\}$ incur a cost to the individual sending them of $c_M > 0$, with each message interpreted as a statement advocating for a particular state. Choosing to remain silent, sending the empty message $m_\emptyset$, incurs no cost. At the same time as the decision to send a message, agents choose whether or not they will listen to others' messages, incurring a fixed cost $c_R > 0$ if they choose to listen—regardless of the number of messages sent—and no cost if they do not. After messages are sent and observed (by those that listen) the final choice stage begins, and each agent makes their individual choice on the state, y_i.

In summary the complete game timing is as follows: (i) nature determines the state ω; (ii) each agent realizes an interim posterior on the state being A, x_i; (iii) agents simultaneously choose whether to send and/or listen to messages; (iv) agents who chose to listen observe the messages sent by others; and, finally, (v) agents make their choice y_i.

An example of the communication structure is given in Figure 1, representing a group of 5 agents. After realizing their signals, agents 1 and 2 choose to send costly messages in $\{m_H, m_T\}$ to the others (represented by arrows pointing away from the agent), while agents 3 through 5 choose to send empty messages $m_\emptyset$. Agents 2 and 4 choose to listen to the messages of others (inward pointing arrows) while the others choose not to listen. Communication only occurs between agents who have made complementary decisions, represented by the bold, directed arrows in the realization: agent 4 observes the messages from both 1 and 2, while agent 2 effectively only observes the message from agent 1. Information exchange

[11] Breaking symmetry would serve to make one of the two options initially focal, either through greater initial likelihood or through better information upon it. If we relax this assumption, or the ex ante symmetry in the state, then the absence of messages becomes informative. Herein, my focus will be on symmetry being broken via private information and messages, rather than ex ante.

[12] The present model represents one symmetric extreme, with the coarsest symmetric message space. The other extreme would be to allow for perfectly informative messages, where $M = [0, 1]$. Both extreme cases are somewhat tractable, and can be characterized by two cutoffs. However, in between, with multiple messages available to advocate for each state, we require more cutoffs to characterize the equilibrium, and the fixed-point calculation becomes somewhat involved.



(A) Decisions (B) Realizations

FIGURE 1. Communication Network

in the model is necessarily bilateral, requiring endogenous decisions by both a sender and a receiver.

2.2. **Equilibrium.** A communication strategy is a pair of functions over the typespace: a message function $\mu_i : X \to M$ and a binary listening decision $\varsigma_i : X \to \{\text{Listen}, \text{Not}\}$. The final choice of each agent y_i, is given by the decision rule $\phi_i : X \times M^n \times \{\text{Listen}, \text{Not}\} \to \Omega$ which maps every information set (indexed by an interim prior x_i, the realized message vector m and the agent's listening decision r) into a final choice of the state.

The solution concept will be Perfect Bayesian equilibrium (PBE) with a double symmetry restriction. The first that all agents use the same strategies in equilibrium, the second with regard to symmetry in type-specific actions about $x_i = \frac{1}{2}$. In order to clearly define this second restriction, I first define the Bayesian content of each message. Given a message strategy μ, define ν the posterior on the state being A for an agent who has observed only the message $m_j \in M$:

$$\nu(m_j; \mu) := \frac{F_A\left(\mu^{-1}\left(m_j\right)\right)}{F_A\left(\mu^{-1}\left(m_j\right)\right) + F_B\left(\mu^{-1}\left(m_j\right)\right)}. \tag{2}$$

Our solution concept will be:

Definition (Symmetric Language Equilibrium)**.** A symmetric-language equilibrium $(\mu^\star, \varsigma^\star, \phi^\star)$ is a symmetric PBE of the game such that $1 - \nu\left(\mu^\star\left(x\right); \mu^\star\right) = \nu\left(\mu^\star\left(1 - x\right); \mu^\star\right)$ for all $x \in X$.

The definition forces all equilibria to have symmetric message content, so that any realized messages have exact antonyms. If an agent with interim posterior 75 percent confidence on state A sends a message m with inferred content $\nu(m)$, they will, according to the symmetry restriction, send the message's antonym (with content $1-\nu(m)$) when their interim posterior on A is 25 percent (a belief that B occurred with 75 percent probability). In this way all meaningful messages exist in pairs with naturally opposite interpretations *(I strongly agree* vs. *I strongly disagree*, *1 star* vs *5 stars*, etc).

The decision rule ϕ_i in the final stage of the game can be solved using sequential rationality and the consistent belief. If the agent believes A more likely than B, it is optimal to choose A, if they believe A less likely it is optimal to choose B.[13] The SLE definition requires that agents update from received signals according to Bayes' rule, so the equilibrium posterior $\lambda : X \times M^n \times \{\text{Listen}, \text{Not}\} \to [0,1]$ is given by:

$$\lambda(x_i, m, r; \mu) = \begin{cases} \frac{x_i \cdot \Pr\{m_{-i}|\omega=A,\mu\}}{x_i \cdot \Pr\{m_{-i}|\omega=A,\mu\} + (1-x_i)\cdot \Pr\{m_{-i}|\omega=B,\mu\}} & \text{if } r = \text{Listen} \\ x_i & \text{if } r = \text{Not} \end{cases}, \tag{3}$$

Where the agent maintains their prior belief if they do not listen and/or observe no messages from others (the second part implied from symmetry about $x = \frac{1}{2}$). Given the interpretation of each message, and independence, we can simplify the listening posterior to:

$$\lambda(x_i, m, 1; \mu) = \frac{x_i \cdot \prod_{j\neq i} \nu(m_j;\mu)}{x_i \cdot \prod_{j\neq i} \nu(m_j;\mu) + (1-x_i) \cdot \prod_{j\neq i}(1-\nu(m_j;\mu))}$$

Given the final decision rule ϕ and the posterior λ, we are left with the problem of solving the first stage. This is characterized simply as

Proposition 1 (Equilibrium Characterization)**.** *In every SLE the sending strategy is characterized by a critical type $\theta^\star \in \left(\frac{1}{2}, 1\right]$, such that all types $x > \theta^\star$ send costly messages with $\nu(\mu(x))$ weakly increasing in x. The equilibrium listening strategy is characterized by a scalar parameter $\rho^\star \in \left[\frac{1}{2}, 1\right)$ such that all types $x > \rho^\star$ choose not to listen.*

Proof. See appendix. □

Corollary 1 (Existence)**.** *An SLE always exists at $\theta^\star = 1$ and $\rho^\star = \frac{1}{2}$.*

Proposition 1 gives us the equilibrium form for the entire typespace through the symmetry restrictions. The types who listen are those least certain about the state, those with interim posteriors $x_i \in (1-\rho^\star, \rho^\star)$, while those sending messages lie in the two regions $[0, 1-\theta^\star)$ and $[\theta^\star, 1]$. With only two costly messages the equilibrium strategy can be summarized without

[13]When agents believe each state equally likely, I assume agents randomize evenly over A and B. Given the density assumption, this only becomes relevant for types at the mass point $x = \frac{1}{2}$.

loss of generality as:[14]

$$\mu(x)=\begin{cases} m_B & \text{if } x<1-\theta^\star \\ m_\emptyset & \text{if } x\in[1-\theta^\star,\theta^\star] \\ m_A & \text{if } x>\theta^\star, \end{cases}$$

and

$$\varsigma(x)=\begin{cases} \text{Listen} & \text{if } x\in(1-\rho^\star,\rho^\star) \\ \text{Not} & \text{otherwise.} \end{cases}$$

The content of messages is determined by the send cutoff used, θ. Referring to equation (2) the equilibrium content of message m_A is given by

$$\nu(m_A;\theta)=\frac{1-F_A(\theta)}{1-F_A(\theta)+F_A(1-\theta)},$$

and by symmetry $\nu(m_B;\theta)=1-\nu(m_A;\theta)$. The information contained in a costly message sent according to the cutoff θ is summarized by the likelihood ratio

$$\eta(\theta):=\frac{\nu(m_A;\theta)}{\nu(m_B;\theta)}=\frac{1-F_A(\theta)}{F_A(1-\theta)}.$$

Given a number of meaningful messages from others, (a,b) messages for A and B respectively, define the interim posterior $\xi\in X$ as the type marking the switch point between a final choice of A or B. Given $a-b$ excess messages for A, and the communication strategy cutoffs θ and ρ, this critical type is given by

$$\xi_{a-b}\left(\theta,\rho\right):=\max\left\{1-\rho,\min\left\{\tfrac{1}{\eta(\theta)^{a-b}+1},\rho\right\}\right\}.$$

That is, the critical point is either the most-extreme listening type ($x=1-\rho$ with excess messages for A, $x=\rho$ with excess messages for B) or the listening agent indifferent in their final choice y_i. All types to the left of this point (agents with information pointing more toward state B or those agents with initial information pointing to B who did not listen) make the final decision $y_i=B$, while those to the right of this point will similarly choose A.

Conditional on $\omega=A$, the probability of receiving a messages for A, and b messages for B from N other agents is given by the trinomial mass function

$$g^N_{a,b}(\theta)=\left(\begin{array}{c} N \\ a,b \end{array}\right)\left[1-F_A(\theta)\right]^a\left[F_A(1-\theta)\right]^b\left[F_A(\theta)-F_A(1-\theta)\right]^{N-a-b},$$

while conditional on $\omega=B$ the probability is $\eta(\theta)^{b-a}\cdot g^N_{a,b}(\theta)$.

[14]Up to message re-labellings.

Given the final decision rule $\phi(\cdot)$, the individual's problem when others use cutoffs θ and ρ, is to pick communication cutoffs (q,r) that solve

$$\begin{aligned}
u^{\star}(\theta,\rho) &= \max_{q,r\in\left[\frac{1}{2},1\right]} \quad 1-\alpha\cdot\sum_{a,b} g_{a,b}^{n-1}(\theta)\cdot F_A\left(\xi_{a-b}\left(\theta,r\right)\right) \\
&+ \quad (1-\alpha)\cdot\sum_{a,b} g_{a,b}^{n-2}(\theta)\cdot\Big[(1-F_A\left(q\right))\cdot F_A\left(\xi_{a-b+1}\left(\theta,\rho\right)\right) \\
&+ \quad (F_A\left(q\right)-F_A\left(1-q\right))\cdot F_A\left(\xi_{a-b}\left(\theta,\rho\right)\right)+F_A\left(1-q\right)\cdot F_A\left(\xi_{a-b-1}\left(\theta,\rho\right)\right)\Big] \\
&- \quad \left[1-F\left(q\right)+F\left(1-q\right)\right]\cdot c_M-\left[F\left(r\right)-F\left(1-r\right)\right]\cdot c_R, \qquad (4)
\end{aligned}$$

where we can condition on $\omega=A$ throughout using symmetry of the problem and strategies.[15]

The best-response listening cutoff is a function only of others send cutoff θ, and not of ρ. The best response listening strategy solves

$$r(\theta)=\frac{\sum g_{a,b}^{n-1}\left(\theta\right)\mathbf{1}\left\{\frac{r(\theta)}{1-r(\theta)}<\eta\left(\theta\right)^{a-b}\right\}-{}^{c_R}/_{\alpha}}{\sum g_{a,b}^{n-1}\left(\theta\right)\left[1+\eta\left(\theta\right)^{b-a}\right]\mathbf{1}\left\{\frac{r(\theta)}{1-r(\theta)}<\eta\left(\theta\right)^{a-b}\right\}}, \qquad (5)$$

where I use the formalization that cutoff values below $\frac{1}{2}$ are interpreted as the agent never listening.[16] The listening decision is continuous and fairly easy to calculate as a function of others' sending behavior θ.[17] In contrast, the best-response send cutoff responds to both the sending and listening behavior of others. The best response is given by

$$q(\theta,\rho)=\frac{\sum g_{a,b}^{n-2}\left(\theta\right)\left[F\left(\xi_{a-b-1}\left(\theta,\rho\right)\right)-F\left(\xi_{a-b}\left(\theta,\rho\right)\right)\right]+{}^{c_M}/_{1-\alpha}}{\sum g_{a,b}^{n-2}\left(\theta\right)\left[F\left(\xi_{a-b-1}\left(\theta,\rho\right)\right)-F\left(\xi_{a-b+1}\left(\theta,\rho\right)\right)\right]}, \qquad (6)$$

[15]The expected value of the variable Z given here as$\sum_{a,b} g_{k_H,k_T}^{N}(\theta)\cdot Z$ is an abbreviated notation for the more formal (but ink-heavier) $\sum_{a=0}^{N}\sum_{b=0}^{N-a} g_{a,b}^{N}(\theta)\cdot X$. To conserve even more ink—though probably not enough—I will henceforth just use $\sum g_{a,b}^{N}(\theta)\cdot X$.

[16]So consider the actual best response cutoff as $\max\left\{\frac{1}{2},r(\theta)\right\}$.

[17]It does not have a continuous derivative because the indicator functions nest the number of messages necessary for the critical listener to change their decision. As θ varies some critical listeners will require multiple messages and the summations will effectively be over a smaller number of (a,b) pairs.

Similar to equation (5), the message-sending best response is used with the formalization that values above 1 imply the agent never sends messages.[18,19]

The best responses constructed above lead to the equilibrium result:

Proposition 2. *All SLE are fixed points of the one-dimensional continuous function* $q_r(\theta) := q(\theta, r(\theta))$.

Generically, there are an odd number of equilibria, and there is always a fixed point at $\theta^\star = 1$, per Corollary 1. My focus will be on the two equilibrium extremes, the fixed-point $\theta^\star$ where q_R first crosses the 45° line (the equilibrium with the most sending behavior) and the fixed point where $\theta^\star = 1$, the silent/no-communication equilibrium.

The individual's maximization problem given in 4 stands in contrast to the social planner's problem (enforcing the same symmetry restrictions) of choosing a communication strategy for the group (θ, ρ) that solves

$$\begin{aligned} W &= \max_{\theta,\rho\in\left[\frac{1}{2},1\right]} 1 - \sum g_{a,b}^{n-1}(\theta)\cdot F\left(\xi_{a-b}\left(\theta,\rho\right)\right) \\ &- \left[1-F\left(\theta\right)+F\left(1-\theta\right)\right]\cdot c_M - \left[F\left(\rho\right)-F\left(1-\rho\right)\right]\cdot c_R. \end{aligned} \tag{7}$$

There are two main differences between (4) and (7). The first-order effect is the change in individual benefits of sending and listening, with weights α and $1-\alpha$, respectively, in the individual's problem, compared to unity in the planner's problem. That is, individuals do not fully internalize the benefits from their own decisions on others. In addition, there are second-order effects, as the social planner is able to choose the cutoffs jointly, where the individual takes others' sending/listening/updating as given, and they are unable to influence these decisions. Intuitively, individuals send and acquire less information than the optimal level, this in turn reduces the value of acquiring and sending information, further pushing the equilibrium from the optimal level.[20]

Proposition 3 (Welfare)**.** *All SLE for the game with positive costs for communication are inefficient, with higher send cutoffs* $\theta^\star$ *than the social planner's choice.*

Proof. See appendix. □

[18]That is, the true best response cutoff is $\min\left\{1, q\left(\theta,\rho\right)\right\}$. N.B. where the function in (6) is undefined when the numerator is 0, the best-response is to never send. Similarly for (5), where undefined the best-response is never to listen.

[19]The best-response $q(\theta,\rho)$ assumes the other $n-1$ agents update according to the cutoff θ, which will be a necessary condition in equilibrium.

[20]In the limit, as the communication costs go to zero, the planner and most-informative equilibrium solutions coincide. The limiting-cost solution is to use the three available messages optimally, and the message $m_\emptyset$ is sent in the non-empty interval $[1-\theta_0, \theta_0]$, and every agent-type that can feasibly change their mind given $n-1$ messages listens.

Notice that the above result only specifies less *sending* in equilibrium than the planner's solution. When the costs for listening are very low, even those with very high confidence in their information might pay to listen. As the send cutoff θ increases, the probability of receiving *any* message decreases. However, conditional on a message being received, the inferred *content* increases with θ, as messages are sent by group members with better information. Therefore, more group members can listen even as less send, given small enough listening costs. However, the expected amount of information exchanged is always lower.[21]

An obvious question is whether we can subsidize the communication channels to produce the planner's solution $(\tilde{\theta}, \tilde{\rho})$. Fortunately, the answer is yes, and it can be achieved with a fairly simple policy.

Corollary 2. *The planner's solution is attainable an an equilibrium outcome by making ex ante transfers and subsidizing the communication channels.*

The result comes directly from the proof of Proposition 3, and stems from the fact that an equilibrium of the game with send costs $\frac{1-\alpha}{n-1} \cdot c_M$ and listening costs $\alpha \cdot c_R$ has communication cutoffs that coincide with the planner's solution. As such we can run a budget-balanced mechanism that extracts the expected communication cost differences from each agent ex ante, and then directly subsidizes group members using each specific channel to achieve the desired cost environment.[22]

Proposition 2 and the above Corollary make clear that if we can commit before realizing signals to subsidize communication (a subscription process, paying dues, re-routing common resources, etc.), then we might be able to improve welfare. However, even with the optimal subsidy, there are still issues with equilibrium selection, as subsidies do not eliminate the no-communication outcome. The benefits from subsidies will therefore depend on equilibrium selection, a question that provides additional motivation for an experiment.

3. Experiment Design

In this section I will attempt to illustrate the model. In order to get more done with fewer words, the illustration uses the chosen parameters for my experiment below. I first discuss the parametrization in the language of the model, and then discuss the equilibrium and welfare predictions. Finally, I discuss some specifics on the experiment, describing the subject-pool and procedures followed.

[21] If the message space were richer, and allowed for full-revelation of private information, then the equilibrium listen cutoffs would necessarily be lower than the social planner's under the same costs.

[22] A more complicated system of transfers with ex ante and ex post transfers can be constructed so that the budget is balanced for all realizations. This mechanism requires extracting additional ex ante transfers, and returning excess funds differentially to those sending and listening to maintain the same incentives.

3.1. **Parametrization.** I start with a group of five individuals ($n = 5$), where the preferences for the rest of the group and the individual are set to have equal weight, so $\alpha = 1 - \alpha = \frac{1}{2}$. The distribution for F_A has a mass point of size $1 - q = \frac{1}{2}$ for the type that is completely ignorant on the state's realization ($x_i = \frac{1}{2}$), while the density for all other types $x_i \in [0, 1] \setminus \frac{1}{2}$ is proportional to x_i, so that $f_A(x_i) = x_i$.[23] The signal distributions are therefore completely pinned down by

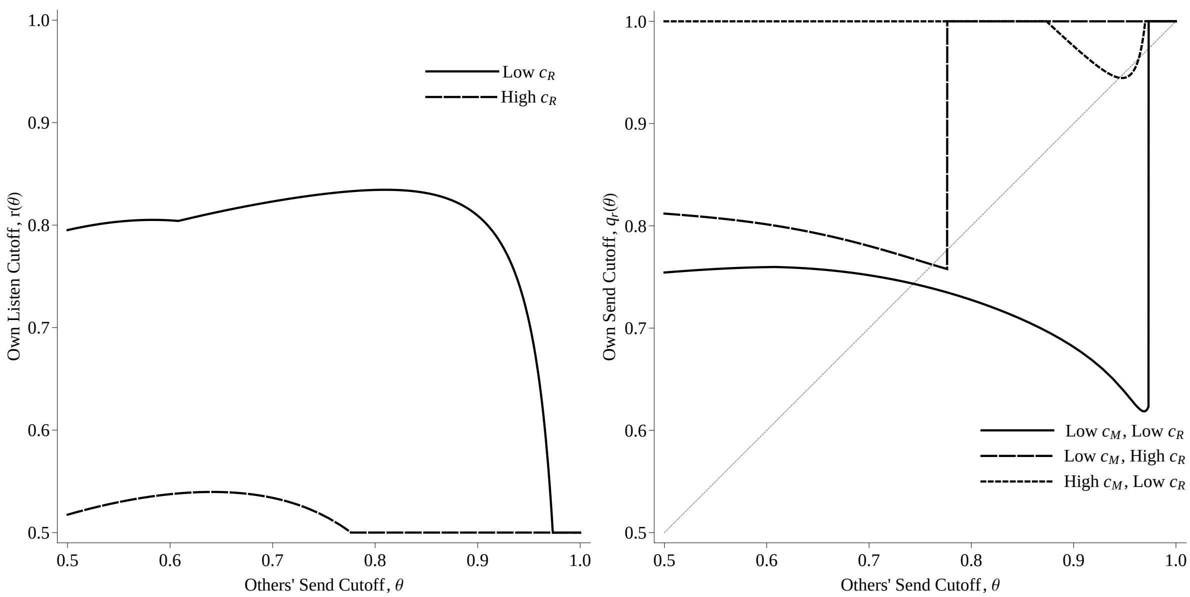
$$F_A(x) = \begin{cases} \frac{x^2}{2} & \text{if } x \in \left[0, \frac{1}{2}\right) \\ \frac{5}{8} & \text{if } x = \frac{1}{2} \\ \frac{1+x^2}{2} & \text{if } x \in \left(\frac{1}{2}, 1\right] . \end{cases} \tag{8}$$

With no communication, the representative group member makes the correct final choice with probability five-eights: one-eighth of the subjects have information that favors the incorrect state ($x_i < \frac{1}{2}$), while half the group members at the ignorant type will guess incorrectly. Individual rationality implies that communication must serve to increase choice accuracy (the probability the final choice is correct) above this level.

I will examine the equilibria when the costs c_M and c_R are either *Low* or *High*, values of either 0.025 or 0.125, respectively. Communication costs therefore can be understood as a 2.5 percent or 12.5 percent penalization to the prediction probability. Given the preference weight $\alpha = \frac{1}{2}$, the *effective costs* are doubled for the individual: it is optimal to send with high costs only if you increase the probability others make a correct choice by at least 25 percent; similarly, it is optimal to listen with high costs only if the expected message increases the probability you make the correct choice by 25 percent. With low costs, the necessary gains to the prediction are just 5 percent for each decision.

3.2. **Best Response and Equilibrium.** The best-response cutoffs are illustrated in Figure 2. The first panel illustrates the best-response listening cutoff $r(\theta)$, for *High* and *Low* listening costs, as a function of the send cutoff used by others, θ. When costs for listening are *Low* and the other group-members use send cutoffs between 0.5 and 0.9, the acquisition best response is fairly flat, listening to others whenever the interim posteriors is between 0.2 and 0.8. There are two competing effects as θ increases. The first is negative, a provision effect. As send cutoffs increase the probability of receiving a meaningful message, $F_A(1-\theta) + 1 - F_A(\theta)$, decreases. The second, an *information effect*, is positive. As send cutoffs increase, the information content of each message, summarized by the likelihood ration $\eta(\theta) = \frac{1-F(\theta)}{F(1-\theta)}$, increases. The information effect dominates the provision effect when $\theta \approx \frac{1}{2}$, but as θ gets larger and larger, the information effect eventually becomes negligible and the negative

[23]See section 3.4 for details on how this distribution is designed to be easy for subjects to understand.



(A) Listen best response $r(\theta)$ (B) Send best-response $q_r(\theta)$

FIGURE 2. Best Responses

provision effect dominates. This can be seen in the fairly rapid decline in listening behavior once others' send cutoffs increase above 0.9.[24] Those with good private signals stop listening as they believe it unlikely that they will receive messages contradicting their prior, so the best-response listening-cutoff drops rapidly until even those with no information stop listening. When listening costs are *High* (the dashed line), because the benefit to listening is the same for any particular θ, the critical type indifferent over the listening decision is much closer to 0.5 than under low costs. Because the critical listening type is so uncertain on the state, just a single meaningful message needs to be sent for their choice to switch for all cutoffs $\theta \in (\frac{1}{2}, 1]$. For a similar reason, the information effect is quickly dominated by provision effects: more information content in each message does not affect the listeners' choice behavior, all that matters is the provision of a single correct message.[25] As such, if the send cutoffs used by others exceeds 0.78 the provision is too low, and the best response for all types under *High* listening costs is to never listen.

[24]The discontinuity in slope comes with the critical listener requiring 1 instead of 2 messages to change their decision.

[25]This is potentially interesting as an explanation for coarse message environments. Suppose refined messages are possible, but cost a small amount more than a coarse message. If the equilibrium send cutoff is greater than the listen cutoff, only one excess message is required for all listeners to choose that outcome. More refined messages create benefits only in breaking ties with conflicting opinions: these situations are of second-order importance and occur with rapidly decreasing probability as the send-cutoff increase. In this way the coarsest message space may be favored, even if finer messages were available.

The second panel in Figure 2 illustrates the send-cutoff as a best-response (incorporating the optimal listening behavior). The figure illustrates the best-response send cutoff $q_r(\theta) = q\left(\theta, r\left(\theta\right)\right)$ under the different cost environments.[26] The horizontal-axis is again the send-cutoff used by other group members, θ, and the vertical-axis is the best-response send cutoff. When others use send cutoffs close to 0.5—so that only marginal information in favor of either state is needed to send a message—many messages will be provided by others, and the best-response is for agents to use a higher send cutoff than others, to send less frequently. When costs for sending are *Low* the response is to send when the interim prior is above 0.75–0.80, whereas when the send costs are *High,* the best-response is to never send if others provision is high ($\theta < 0.85$). As others' cutoffs increases the value of the individual sending increases, and best-responding agents use lower send cutoffs (sending messages more often). However, sending and listening behavior interact, so individuals will only provide if others listen. This interaction is clearest when looking at the sending best response for low c_M for the differing listening costs. When the listening cost c_R is low, each best-responding individual increases their message sending behavior (decreasing the send cutoff) as others send less, until $\theta \simeq 0.95$, when the number of listeners falls to zero. When c_R is high, the best-response jumps to never sending at 0.78, where the $(1-q)$ mass of individuals at $x_i = \frac{1}{2}$ stop listening.[27]

The SLE of the game are defined by the send cutoffs where $q_r(\theta) = \theta$, the points where the best-response crosses the $45°$ line. Despite fairly large differences between the two best responses when sending is cheap, the most informative equilibria have fairly similar predictions, where the equilibrium difference is primarily derived from the much smaller fraction of group-members listening when c_R is *High*.

In contrast when sending costs are *High* the best-response is to never send unless others use very high cutoffs, and then only when the listening costs are low. When the cost of listening is also *High*, it is never a best-response to send at any confidence level, so no communication is the only equilibrium outcome. With *High*-sending and *Low*-listening costs it is a best-response is to never send unless others cutoffs are above 90 percent, with the cutoff used thereafter decreasing through a greater likelihood that the individual's message is the only one, and subsequently pivotal to the listeners. The equilibrium with *High* send costs and *Low* listening costs is to send at approximately 95 percent confidence or above.

[26]Note that given *High* costs for sending *and* listening the best-response the best response is a flat line with a best response of never sending, regardless of others send cutoff.

[27]There is a mixed-strategy equilibrium here with those at the ignorant interim prior randomizing whether to listen or not, though I will not focus on these equilibria.

TABLE 1. Theoretical Send and Listen Cutoffs

Cost Treatment			**Equilibrium**				**Planner's Solution**			
Label	$\frac{c_M}{1-\alpha}$	$\frac{c_R}{\alpha}$	$\theta^\star$	$\rho^\star$	$\Upsilon^\star$	$\Upsilon^\star - C^\star$	$\tilde{\theta}$	$\tilde{\rho}$	$\tilde{\Upsilon}$	$\tilde{\Upsilon} - \tilde{C}$
L-L	0.05	0.05	0.743	0.830	94.1%	80.1%	0.662	0.880	99.3%	83.7%
H-L	0.25	0.05	0.945	0.727	33.2%	20.3%	0.714	0.872	97.3%	67.7%
L-H	0.05	0.25	0.762	0.510	67.1%	31.3%	0.655	0.711	93.6%	43.4%
H-H	0.25	0.25	1.0	0.5	0.0%	0.0%	0.709	0.715	91.7%	27.1%

For each cost environment the equilibrium predictions for communication behavior are given in Table 1 where $\theta^\star$ is the smallest fixed point of $q_R(\theta)$, and $\rho^\star = r(\theta^\star)$.[28] Additionally, the table also provides the social planner's cutoffs, which are derived by solving the problem in (7) and are given in the columns titled $\tilde{\theta}$ (planner's send cutoff) and $\tilde{\rho}$ (planner's listen cutoff).

3.3. **Prediction Rates and Welfare.** In order to assess the effects of the cost environment I will focus on two efficiency measures, one for prediction and the other for welfare. For *prediction efficiency* I will examine the following measure

$$\Upsilon(\theta,\rho) = \frac{\Pr\{y_i = \omega\,|\theta,\rho\} - \Pr\{y_i = \omega\,|\text{No Communication}\}}{\Pr\{y_i = \omega\,|\text{Zero Cost Planner's Solution}\} - \Pr\{y_i = \omega\,|\text{No Communication}\}}.$$

This metric examines the extent to which the group exchanges all the information available, where 0% is the *No Communication* prediction rate, while 100% is the statistical upper bound on prediction, given the message environment and symmetry. The second metric will seek to measure *payoff efficiency*, reflecting the expected utility, where I again measure this relative to *No Communication* lower-bound and the zero-cost planner's solution upper bound. We need to penalize the prediction efficiency by removing the expected costs incurred. Given the cutoff-pair (θ,ρ) the expected communication cost to the individual (measured in prediction efficiency units) is:

$$C(\theta,\rho) = \frac{[1 - F(\theta) + F(1-\theta)] \cdot c_M + [F(\rho) - F(1-\rho)] \cdot c_R}{\Pr\{y_i = \omega\,|\text{Zero Cost Planner's Solution}\} - \Pr\{y_i = \omega\,|\text{No Communication}\}}$$

Our *payoff efficiency* measure will then just $\Upsilon(\theta,\rho) - C(\theta,\rho)$.[29]

[28]In the table, and henceforth, I will refer to all treatments by a shorthand label of *"Send-Cost–Listen Cost*," so that by *"H-L"* I refer to the treatment with *High* send costs and *Low* listen costs.

[29]This is equivalent to measuring payoff differences against the individually rational point with the same normalization as before.

The prediction and payoff efficiencies at both the equilibrium level and under the planner's solution are provided in Table 1 Across all four treatments, the planner's solution (provided in the $\tilde{\Upsilon}$ column) has prediction rates close to the upper bound, with the worst performance in those situations where listening costs are large, though the prediction loss is small. In contrast, in the equilibrium prediction column (titled $\Upsilon^{\star}$) the worst prediction rates stem from high costs to sending. With high send costs and low listening cost, the equilibrium incorporates only a third of the information available, and if both costs are high, no information exchanged at all. Examining the payoff efficiencies, a similar picture emerges. The equilibrium welfare ordering (given by $\Upsilon^{\star} - C^{\star}$) across the four cost environments is

$$L\text{-}L \overset{\star}{\succ} L\text{-}H \overset{\star}{\succ} H\text{-}L \overset{\star}{\succ} H\text{-}H \overset{\star}{\sim} \text{No Communication.}$$

In contrast, the planner's solution ($\tilde{\Upsilon} - \tilde{C}$) ranks the treatment outcomes as

$$L\text{-}L \tilde{\succ} H\text{-}L \tilde{\succ} L\text{-}H \tilde{\succ} H\text{-}H \tilde{\succ} \text{No Communication.}$$

The planner's solution creates higher welfare with *High* sending costs and *Low* listening costs than the reverse case, in contrast to the equilibrium ranking. Given *Corollary* 2, this parametrization indicates much larger gains from subsidies to communication in the *H-L* environment. If agents were able to commit to making initial transfers to subsidize the communication channels, payoff efficiency could nearly triple from 20 percent of the maximal level to just under 70 percent. Similarly, in the *H-H* environment the optimal policy increases the payoff efficiency by a substantial amount. In contrast, when the send costs are *Low*, the gains from the communication subsidies are much smaller. In *L-H* the equilibrium payoff efficiency is approximately 30 percent, where the optimal transfer would boost it to just under 45 percent. In the *L-L* environment the gains from intervening are almost negligible.

3.4. **Laboratory Experiment Specifics.** The experiments that test the above theoretical predictions were conducted at the Center for Experimental Social Science's laboratory at New York University, and followed standard methods for recruiting undergraduate students from the university population. The experimental interface was programmed using the *zTree* software documented in Fischbacher (2007), with programs and code available from the author by request.[30]

I utilize a between-subject design with the costs for communication (c_M and c_R) as the treatment variables fixed across sessions in a 2×2 factorial pattern (*High* and *Low* costs for

[30]Again, as is standard in economic experiments, all subjects provided informed consent, and the experiment has no deceptive components. Instructions for a representative treatment are available in supplemental appendix C, alongside screenshots of the interface used.

each, as above). Each treatment consists of a particular cost environment, and had three experimental sessions, for 12 sessions total.

Eight sessions recruited 20 unique subjects, while four sessions recruited 15 unique subjects, for a total of 220 subjects. Sessions lasted approximately an hour and a half, with average payments across subjects and treatments of \$25.43. Each session is comprised of 30 identical rounds, in each of which 5 subjects are randomly and anonymously matched together into a group $\mathcal{G}$, where I will treat each round as a one-shot game.

The distributions F_A and F_B induced in the experiments were chosen to have a cognitively simple form, while the large mass point is used to increases the incentives for communication. Signals are drawn identically for every subject across all treatments. With probability $\frac{1}{2}$ each subject received an informative signal, otherwise drawing a null signal. Informative signals are drawn as follows: (i) A subject is given a private draw x_i from an independent, uniform distribution on $[0, 1]$, expressed as a percentage.[31] (ii) The computer then secretly drew another random number x_i' from the same process, which the subject was not informed of. (iii) If $x_i < x_i'$ the computer provides the agent with the true state of the world, ω. (iv) If $x_i \geq x_i'$ the subject is told the complement of the true state.

The experimental private signals are therefore pairs $(x_i, \omega_i') \in [0, 1] \times \{A, B\}$. Given a signal $\sigma_i = (x_i, A)$ the interim posterior is:

$$\begin{aligned}\Pr\{\omega = A\,|\sigma_i = (x_i, A)\} &= \frac{\Pr\{\sigma_i = (x_i, A)\,|\omega = A\}}{\Pr\{\sigma_i = (x_i, A)\,|\omega = A\} + \Pr\{\sigma_i = (x_i, A)\,|\omega = A\}} \\ &= \frac{x_i}{x_i + (1 - x_i)} = x_i\end{aligned}$$

The signal process is therefore constructed so that the provided value x_i is the probability the provided state ω' is correct, and this intuition was explicitly given to subjects to aid their understanding.[32] The distribution of interim posteriors is therefore the F_A distribution (and the mirrored F_B distribution) given in (8).

In each round t, subject i earns 100 experimental points if their final choice on the state y_{it} is correct, and 25 points for each of the other four group members who select the correct state. *Low* costs for communication are 5 points, and *High* costs 25 points. To prevent negative points in a round, each subject receives an endowment of 50 points at the beginning

[31] Represented to four decimal points, i.e. 99.99%.

[32] Subjects were provided with all of the signal distribution details above, but to aid understanding, all numbers were additionally expressed as "accuracies." That is if the received signal was (x_i, B) and $x_i < \frac{1}{2}$, then the interface informed subjects that their signal accuracy was $1 - x_i$ on state A. If the signal was (x_i, B) and $x_i > \frac{1}{2}$ then the interface provided a signal accuracy of x_i on state B. In addition the experimental instructions use *Heads* and *Tails* as the two state realizations, rather than *A* and *B*.

of a round. The point payoff for subject i in round t is therefore given by:

$$u_{it} = 50 + 100 \cdot \mathbf{1}\{y_{it} = \omega_t\} + \sum_{j \in \mathcal{G}_t \setminus \{i\}} 25 \cdot \mathbf{1}\{y_{jt} = \omega_t\} - \text{costs}_{it} \tag{9}$$

where ω_t is the true state and $\mathbf{y}_t$ is the 5-dimensional vector of final choices for all members of group $\mathcal{G}_t$. This payoff form directly corresponds to the preferences given in Equation (1), with a scaling constant of 200, a weight $\alpha = \frac{1}{2}$, and an offset of 50 to prevent negative values. Points won net of the costs incurred are recorded for each of the 30 rounds, and at the end of the experiment, three random rounds were selected for payment. Each selected round was paid using a lottery for \$7 dollars, where the probability of winning the lottery is equal to $\frac{\text{Points won}}{250}$. This payment device was chosen to induce risk-neutrality (theoretically) over payoffs (cf. Roth and Malouf, 1979). Additionally, all subjects received a show-up fee of \$10.

In the baseline treatment, with low costs for both sending and receiving messages, the cost of always listening and always sending represents an expected loss of \$0.84 from the possible \$21 at stake. In the treatment where each cost is high, incurring both costs represents a \$4.20 expected cost. Because of the separability of the two communication decisions, the send costs effectively represent the term $\frac{c_M}{1-\alpha}$ from the theory, the physical cost of sending divided by the preference weight placed on others' choices. Similarly, the listening costs represent the true cost of listening weighted by how much the agent cares about their own individual choice, the term $\frac{c_R}{\alpha}$. So high costs for listening represent environments where either individual's incentives for providing the correct decision are low or the true cost of listening is large. High costs for sending represent either weak preferences for the correct decisions of others or large frictions to information provision. For notational ease though I will refer to the costs simply as c_M and c_R and omit the preference scaling factor α.

The experiment uses a strategy method for communication: Rather than induce the information type x_{it} and ask subjects whether they wish to send or listen, the interface asks them to specify two communication cutoffs.[33] Subjects choose one cutoff for sending messages, θ_{it}, and one cutoff for listening to messages, ρ_{it}. These cutoffs are expressed as "accuracy" levels to enforce symmetry of the strategy, and are subsequently supplied by subjects as two numbers between 50–100 percent. After specifying cutoffs, agents realize their information x_{it} from the signal process, and messages are sent and received according to their strategy. For example, where a subject specifies a send-cutoff of $\theta_{it} = 0.90$, a message is sent for

[33]The most commonly cited evidence for the equivalence of the strategy method is Brandts and Charness (2000). For a deeper survey of the issue see Brandts and Charness (2009).

the appropriate state whenever x_{it} is above 0.9 or below 0.10.[34] For a specified listen-cutoff $\rho_{it} = 0.80$ the subject will automatically listen to messages sent whenever x_{it} is between 0.20–0.80.

Finally, after the communication stage, subjects make their final choices y_{it}, with all their available information listed on the final screen (their private information x_{it}, their communication decisions, any messages they observed if listening). After the final choices are made for the group, subjects are given feedback on the signals x_{it} received by all five group members, the realizations of the decisions on whether or not to listen and/or send messages by others (but not the cutoffs others specified), and the final choices and point payments for the round. In addition they are provided with a history of their choices and payoffs.

To summarize, the sequence of a standard round is as follows: (i) the subject specifies two cutoffs, θ_{it} and ρ_{it}; (ii) nature flips a fair coin to determine the state ω_t in each group; (iii) subjects realize their signals x_i; (iv) message and listening decisions are made realized according to the the provided cutoffs and realized signal (v) subjects who listened observe the messages sent by others in the group, $\mathbf{m}_t$; (vi) subjects make their final choices y_{it}; and (vii) subjects see feedback for the round.

It is worth emphasizing that the strategy method I employ directly enforces the equilibrium form in Proposition 1. The experiment's aim is to test the comparative static predictions of the model for communication behavior and the resulting prediction/welfare results.

In the next section I assess the degree of over- or under-provision of messages to others, and whether subjects over- or under-acquire information. After establishing the communication behavior, I will then discuss how this behavior affects subjects prediction rates and earnings. I then provide evidence on how subjects interpret the messages they observe, and whether this is affected by the cost environment. In order to provide these additional answers the experiment collects additional incentivized belief data in the final 10 rounds (rounds 21–30). After agents have observed messages if listening, and just before making their final choices, I elicit their cardinal beliefs on the state ω_t using a quadratic-scoring rule (see Nyarko and Schotter, 2002). This data allows me to better assess how subjects react to any observed messages—where the choice data is a binary reflection of the posterior, the elicited beliefs reflect intensity.[35]

[34]The interface forces particular message meanings by choosing the relevant sent message, ruling out the equilibrium where a message "B" means A, and "A" means B.

[35]In order not to affect the strategies significantly, the amount that agents make in the belief elicitation phase is small (subjects can earn at most \$1 from this task), with the belief payment made on a single, randomly selected round from the last 10. The experimental earnings are therefore capped below at the show-up of \$10, and above by \$32, if the subject wins all three lotteries of \$7 and makes \$1 from the belief elicitation.

TABLE 2. Aggregate Results, Last 10 Rounds

Cost Treatment			Experiment					
Label	c_M	c_R	**Sessions**	N_S	$\overline{\theta}$	$\overline{\rho}$	$\overline{\Upsilon}$	$\overline{\Upsilon}-\overline{c}$
L-L	0.05	0.05	3	55	0.778	.709	71.3%	59.6%
					(0.008)	(0.008)	(6.4)	(6.4)
H-L	0.25	5	3	60	0.873	.673	53.2%	36.1%
					(0.008)	(0.008)	(6.2)	(6.2)
L-H	0.05	0.25	3	50	0.816	.601	45.8%	9.4%
					(0.008)	(0.009)	(6.7)	(6.8)
H-H	0.25	0.25	3	55	0.864	.611	14.3%	-28.4%
					(0.008)	(0.008)	(6.4)	(6.5)

Note: The estimates $\overline{\theta}$ and $\overline{\rho}$ are obtained from a random-effect Tobit estimations to account for censored regions at 0.50, and 1.00; estimates of $\overline{\Upsilon}$ and $\overline{\Upsilon}-\overline{c}$ are extracted from random-effect regressions of the points won and net points earned, respectively, on a set of orthogonal treatment dummies, respectively. Standard errors are presented below estimates in parentheses.

4. EXPERIMENTAL RESULTS

4.1. **Sending and Listening Behavior.** The aggregate listening and sending strategies used by subjects in the experiment are provided in Table 2 along with the number of subjects N_S in each treatment's three sessions. The variables $\overline{\theta}$ and $\overline{\rho}$ represent the average cutoffs used across subjects for sending and listening in the last 10 rounds of the experiment, recovered with standard errors using a Tobit model. I use the last 10 rounds to show the average behavior after subjects have become familiar with the game and converged on their preferred level.[36]

Sending behavior exhibits the following aggregate order (where $\succ_{\bar{\theta}}$ represents *more* observed sending of messages):[37]

$$L\text{-}L \succ_{\bar{\theta}}^{\star\star\star} L\text{-}H \succ_{\bar{\theta}}^{\star\star\star} H\text{-}H \sim_{\bar{\theta}} H\text{-}L \succ_{\bar{\theta}}^{\star\star\star} \text{No Sending.}$$

While listening behavior exhibits the aggregate order (where $\succ_{\bar{\rho}}$ represents *more* listening to messages)

$$L\text{-}L \succ_{\bar{\rho}}^{\star\star} H\text{-}L \succ_{\bar{\rho}}^{\star\star\star} H\text{-}H \sim_{\bar{\rho}} L\text{-}H \succ_{\bar{\rho}}^{\star\star\star} \text{No Listening.}$$

For both the listening and sending behavior the theoretical orderings are similar to the observed, with the exception being that the *H-H* treatment is weakly ordered above the

[36]Results are similar for the entire sample, and statistically stronger in terms of the behavior rankings: I use a sub-sample here to try to remove initial learning from the numerical figures.

[37]The number of stars above the relations $\succ_{\bar{\theta}}$ and $\succ_{\bar{\rho}}$ represent significance at the 5, 1 and 0.1 percent levels, respectively. I use the relation $\sim$ to reflect a failure to reject at the 10 percent level.

asymmetric treatment with high costs for the relevant communication variable, though the differences are not statistically significant.[38]

Comparing the aggregate results in Table 2 to the equilibrium predictions in Table 1, we observe a consistent pattern: subjects under-communicate (both listening and sending) when the respective costs for the activity are low, but over-communicate when these costs are high.

Because listening is a best response to the sending behavior, the smaller response to increased costs might be caused by the observed sending cutoffs being different from the equilibrium prediction. Examining the best response map in Figure 2a though, one can see that subjects are still under-listening when costs are low, and over-listening when high: fixing the send behavior of others in each treatment at $\overline{\theta}$ (the aggregate level) the listening best response $r(\overline{\theta})$ is to listen for signals in 0.12–0.88 in the low-listen-cost treatments, and to never listen in those treatments with high costs. Conducting a similar exercise for the sending best response $q(\cdot,\cdot)$, I fix the listening and sending behavior of others at $\overline{\rho}$ and $\overline{\theta}$, respectively. The empirical best response $q(\overline{\theta},\overline{\rho})$ is to never send when costs for sending are high, and to send at approximately 0.70 when send costs are low. So as a best-response, subjects would do better to send more than they do when the costs are low, and would improve their outcomes by communicating less when the costs are high.[39]

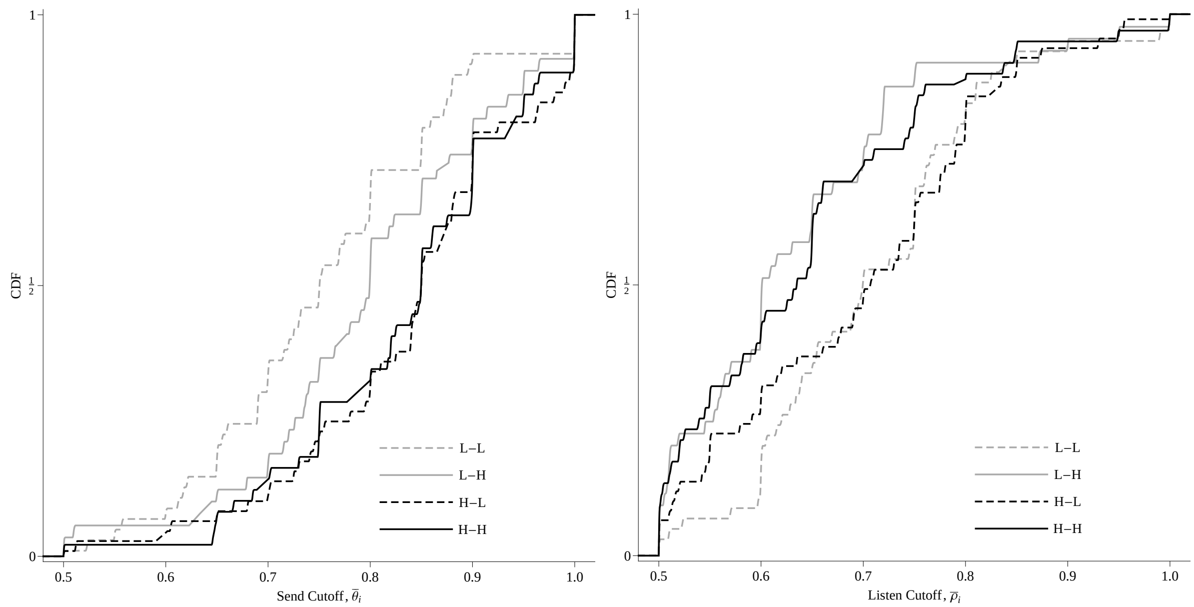
***Result 1*:** Aggregate sending and listening behavior:

- Subjects react to the direct communication costs in the theoretically predicted directions.
- Subjects under-communicate when costs are low, and over-communicate when the costs are high, relative to the equilibrium prediction.
- The patterns of over- and under-communication cannot be rationalized through noisy/empirical best-response.

Variation in strategies used at the subject level are illustrated in Figures 3a and 3b. The figures provide CDFs for subject's average cutoffs in the last ten rounds of the experiment, so the distribution subject-level heterogeneity. Examining the four distributions, the theory again does well in terms of predicting the ordering the send cutoffs. There is a clear stochastic

[38]I discuss subject-level heterogeneity below, but it should be noted that including subject fixed effects reduces the significance of the relations above due to a smaller sample (effectively just N_S instead of $10N_S$), and the above relations are significant at the 20, 10 and 5 percent levels.

[39]Conducting a QRE type exercise cannot rationalize the responses for *High* costs, as errors in play push best response in the opposite direction from the observed differences. Any noise in the final decisions y_{it} must also be much smaller than the noise on communication decisions: errors in final choice reduce the value of communicating information to others. As such a standard QRE approach, similar to the best-response data, moves strategies away from the observed response. See below for an alternative non-Bayesian approach for the under-communication with *Low* costs while the appendix provides a descriptive rationalization through preference heterogeneity.



(A) Sending cutoff, θ (B) Listen Cutoff, ρ

FIGURE 3. Distribution of strategies used

relationship only between extreme environments: subjects in the *High*-send-cost treatments send less than those in *Low* cost treatments (lower cutoffs imply more sending). Subjects listen less in *High*-listen cost treatments than *Low*-listen cost treatments.

However, as the figures make clear, there is a substantial variation in the average cutoffs used across subjects. The standard deviation of the communication cutoffs over subjects is 12–14 percent within the four treatments. This variance in behavior can be contrasted with similar subject-level variance found in experiments based on Crawford and Sobel (1982). In these misaligned-incentive environments heterogeneity has been explained through variance in strategic/cognitive level: some subjects are overly honest or overly credulous in an environment where not fully communicating private information can improve the individual outcomes. However, this strategic tension is not readily applied to my environment, as there is no misalignment in preference—dishonesty is not a strategic motive here, moreover, honesty is directly enforced through the design. Variance in strategy here can be rationalized either by: (i) heterogeneity in subjects' willingness to provide and extract information from the group; (ii) heterogeneity in beliefs about other subjects' listening and sending behavior; and/or (iii) heterogeneity in updating rules, and the subsequent benefits to sending and listening. I will try to provide evidence on the last two, though neither is particularly unnameable to equilibrium analysis. In the appendix I provide details on the necessary conclusions given the first explanation. However, given my results, heterogeneity in preferences for aiding others through increased provision (or honesty) might serve as the better descriptive model for experimental tests of Crawford and Sobel (1982).

***Result 2*:** Subjects' communication cutoffs exhibit a large variance, which is not well explained by variation in subjects' conjectures about others strategic reasoning.

In terms of individuals converging to a single strategy, a total of 42 percent of subjects used an unchanging cutoff throughout every one of the final ten rounds.[40] A minority of subjects do exhibit substantial variation in the cutoffs they use across the entire experiment, and act as if they are randomizing between listening/not with certainty and sending/not with certainty. However, the general pattern is for reduced variability through the session. In the first 10 rounds the standard deviation within subject is 0.122 for the send cutoff and 0.146 percent for the listening cutoff. These figures decrease to 0.066 percent and 0.089 percent, respectively, in the last 10 rounds.

Many subjects in the experiment choose cutoffs at the very extremes, at interim priors of 0.5 and 1.0. Across all treatments a total of 27 subjects (12.3 percent) specify listening cutoffs of 0.5 in every one of the last 10 rounds, so that they never listen to messages. Similarly, a total of 30 subjects (13.6 percent) specify send cutoffs of 1.0 in all of the final 10 rounds, so that they never send messages. The intersection between these two groups is 21 subjects (9.5 percent), those who entirely disengage from communication, never sending and never listening in the last ten rounds.[41] These results are illustrated in Figures 3a and 3b by the large jumps at 1.0 percent and 0.5 respectively.

In the other direction, we can look at those who specify cutoffs to always send or always listen, $\theta = 0.5$ and $\rho = 1.0$, respectively. In total just 3 subjects specify cutoffs corresponding to always listen (1 in a *High* listening-cost treatment) while a total of 5 subjects choose to always send (2 in a *High* send-cost treatment).[42]

Analyzing the dynamics of individual subjects' behavior over time I find some evidence for learning. For the listening decision, the theory indicates three payoff tensions through which subjects might learn: the explicit costs incurred through listening; the implicit cost from a message misinforming; and the benefit that others' messages lead to a better decision. For the send decision, the theory motivates five payoff tensions: the explicit cost for sending a message; the implicit cost of misinforming; an audience size effect (if others do not listen, sending is less valuable); the provision of messages by others; and the benefit that a provided message leads to a better decision for other group-members. The appendix provides details

[40]This numbers grow to 58 percent when we narrow to just the last 5 rounds.

[41]By treatment these 21 no-communication subjects are divided as : 3 in *L-L*; 5 in *L*-H; 7 in *H-L* ; 6 in *H-H* .

[42]The intersection is entirely in the *L-L* treatment, and is 2 subjects.

from regressions on subject's changes in their communication cutoffs in a dynamic sense. I summarize the main learning results:

***Result 3*:** Sending and listening dynamics:

- Subjects strongly react to rounds without sent messages, and reduce their listening behavior substantially.
- There is a strong reaction to the costs incurred from sending, with subjects increasing their send-cutoffs following rounds in which they sent; however, subjects do *not* react to the provision of messages by others, and there is minimal response to others not listening.

4.2. **Message Interpretation.** Having characterized the strategic behavior in the first stage of the game, the second part of my analysis focuses on how subjects update their beliefs. Below I provide estimates of a message inference parameter using two distinct dependent variables. Though the data in both cases is quite noisy I use theory to help me isolate the signal component—removing data that contains almost no signal. Given this sample selection, it is somewhat gratifying that two estimates (which use independently elicited dependent variables) agree in terms of level, where both indicate a non-Bayesian response, with subjects under-weighting the information contained in messages they have received, relative to the weight on their private information.

If subjects update in a Bayesian manner, each received message should carry a fixed information payload, summarized by the theory parameter η, the likelihood ratio of receiving a correct message to that of an incorrect message. Given a messages for *A*, and b messages for *B*, there are $\Delta m = a - b$ excess messages for A. So, in a specific round t, if subject i receives Δm_{it} excess messages, and possessed the initial interim prior on A of x_{it}, the Bayesian posterior on the correct state being A is given by

$$\lambda_{it} = \frac{x_{it} \cdot \eta^{\Delta m_{it}}}{x_{it} \cdot \eta^{\Delta m_{it}} + (1 - x_{it})}. \tag{10}$$

Using the above equation to structure the data, I estimate the value of $\xi(\eta) = \frac{\eta}{\eta+1}$ for each treatment. Transforming η in this manner provides an intuitive value: the interim prior $\xi \in X$ (a confidence on A being the correct state) that is indifferent in their final choice *if they had observed a single excess message for state* B. Subjects with types lower than ξ should select $y_i = B$, while subjects above ξ should select $y_i = A$.

I estimate the parameter $\xi(\eta)$ using two methods under a common parametric assumption on the econometric error: (i) a Probit model using the final choices y_{it}; and (ii) a regression using the elicited beliefs λ_{it} from the final 10 rounds. Both methods will assume that the

TABLE 3. Message Informational Content

Type	**Parameter**	***L-L***	***H-L***	***L-H***	***H-H***
Estimates:	$\xi\left(\widehat{\eta}_P\right)$	0.749	0.715	0.744	0.693
		(0.019)	(0.019)	(0.020)	(0.019)
	N_O	74	59	43	37
	$\xi\left(\widehat{\eta}_B\right)$	0.724	0.728	0.698	0.743
		(0.14)	(0.016)	(0.018)	(0.019)
	N_M	112	82	88	60
Equilibrium:	$\xi\left(\eta^\star\left(\theta^\star\right)\right)$	0.872	0.973	0.881	1.000
Empirical:	$\xi\left(\eta^\star\left(\overline{\theta}\right)\right)$	0.889	0.937	0.908	0.932

Note: Standard errors are given in parentheses below estimated values. N_O is the number of rounds where the signs of $\log\left(\frac{x}{1-x}\right)$ and Δm_{it} are opposed in sign. N_M is the number of rounds with a positive number of messages during belief elicitation. The transformation $\xi(\eta) = \frac{\eta}{\eta+1}$ represents the indifferent type given a single message for T.

message content for individual i in round t is given by the following econometric identity: $\eta_{it}= \eta \cdot \epsilon_{it}$, where ϵ_{it} is a log-normal iid error.

For the Probit approach I use the theoretical condition that the group-member is indifferent between choosing *A* or *B* when $\lambda_{it} = \frac{1}{2}$, and an agent strictly prefers the final choice y_{it} =*A* if $\lambda_{it} > \frac{1}{2}$. Equation (10) can be transformed so that a choice for *A* is made whenever

$$\begin{aligned} & \log\left(\frac{x_{it}}{1-x_{it}}\right) + \Delta m_{it}\log\left(\eta_{it}\right) && > 0 \\ \Rightarrow\quad & \frac{1}{|\Delta m_{it}|}\log\left(\frac{x_{it}}{1-x_{it}}\right) + \frac{\Delta m_{it}}{|\Delta m_{it}|}\log\left(\eta\right) + \log\left(\epsilon_{it}\right) && > 0. \end{aligned} \tag{11}$$

By modeling the error ϵ_η as a log-normally distributed, we could in principle run a Probit estimate on the entire sample and recover an estimate of $\xi(\eta)$ from the coefficient on the $\frac{\Delta m_{it}}{|\Delta m_{it}|}$ term. However, stronger identification of the message content occurs in the sub-sample where the signs of $\log\left(\frac{x_{it}}{1-x_{it}}\right)$ and Δm_{it} are opposed.[43] That is, we can best understand the content of messages by examining when people change their opinion given *conflicting information* from others—excluding clearly irrational behavior. Given an initial signal that makes *A* seem more likely, but receiving messages from others indicating *B*, which state is chosen? The estimates of the critical type assessed using the Probit method are reported in Table 3 in the row labeled $\xi\left(\widehat{\eta}_P\right)$, and are determined from the sub-sample where messages and the subject's private information are in opposition. The count of subject-rounds in the sub-sample is provided in the N_O row.

[43]Outside of this sample, identification is only provided for the sample variance of ϵ_η (scale is identified here).

For the second estimation method I use the incentivized belief elicitation from the last ten rounds. Each subject, with initial information type x_{it} and Δm_{it} excess messages for state *A* enters their belief λ_{it} in the each round from 21 to 30. Rearranging and adding the error term to Equation (10) we have the following separable equation,

$$\frac{1}{\Delta m_{it}}\left[\log\left(\frac{\lambda_{it}}{1-\lambda_{it}}\right)-\log\left(\frac{x_{it}}{1-x_{it}}\right)\right]=\log\left(\eta\right)+\log\left(\epsilon_{it}\right). \tag{12}$$

We can therefore assess the model by regressing a constant on the left-hand side of (12), and recover an estimate of $\xi\left(\widehat{\eta}_B\right)$ from treatment dummies. Again, to isolate the signal, I use a sub-sample of the data defined by those subjects who *receive* a non-zero number of excess messages, $|\Delta m_{it}|>0$.[44] Many subjects' response to the elicitation procedure is to specify beliefs near the boundary, which leads to large LHS magnitudes. I therefore exclude beliefs with values below 1 percent and above 99 percent, in addition I drop all belief observations that move in the wrong direction from the observed message.[45] The estimates of the critical-type from elicited beliefs are given in the row labeled $\xi\left(\widehat{\eta}_B\right)$, where the number of subject-round observations in the sub-sample is given by N_M (non-zero excess messages for A, beliefs move in correct direction and not provided at the boundary).

In order to provide some benchmarks to compare to the obtained estimates against the table also indicates the critical type indicated by equilibrium. When agents use a send-cutoff of θ, the Bayesian content of each message is determined by the likelihood ratio $\eta^{\star}(\theta)=\frac{1-F_A(\theta)}{F_A(1-\theta)}=\frac{1+\theta}{1-\theta}$. So the indifferent type is given by $\xi=\frac{1+\theta}{2}$. Table 3 reports the indifferent type ξ agent under both the equilibrium message content, $\eta^{\star}\left(\theta^{\star}\right)$, and as a best-response to the experimentally observed send cutoff, $\eta^{\star}(\overline{\theta})$.

The estimates for how subjects understand messages indicate a consistent under-attribution. Subjects who observe messages contradictory to their private information switch their choices less often than they should. The estimates suggest that agents choose to go with their own information when they have 75 percent confidence or above, and with the message from other group members when they are at lower confidence levels. This is compared with the Bayesian reaction, which is to only go with private information when it is at 90 percent confidence or above.

[44] Of the 1,515 subject-round pairs with beliefs collected and no observed messages (so the belief should be $\lambda_{it}=x_{it}$), just over a half (793) provide a belief within 1 percent of the interim prior they received. Of the remaining 722 observations, 341 specify a degenerate belief of either 0 or 100%, while 44 choose $\lambda_{it}=\frac{1}{2}\neq x_{it}$. These figures provide an out-of-sample indication of the noise within the belief estimations and motivate my exclusion of the boundary belief data.

[45] For example, if an agent with an interim prior of 0.6 observes a message for *B* and moves to a higher confidence on *A*; or receives a message for *A* and moves to a lower point.

***Result 4*:** Subjects under-attribute informative-content to the observed messages, relying on their private information too much.

4.3. **Welfare.** In this section I detail the aggregate and subject-level welfare by treatment. Similar to the analysis of communication behavior, I first demonstrate that there are significant differences across treatments at the aggregate level. I then look at subject-level variation and demonstrate that the differing cost environments have a precise ranking from a welfare perspective. As in the theory section my focus is on two outcome measures: First, the observed group prediction efficiency $\bar{\Upsilon}$, illustrating whether subjects are faring better with communication than without. Second, the ex ante utility, which accounts for the expected communication costs, $\bar{\Upsilon} - \bar{C}$, measured in prediction efficiency units. Table 2 provides aggregate details on both measures, where the figures are recovered from regressions.[46]

Inspecting the $\bar{\Upsilon}$ column, we observe a significant drop in prediction between *L-L* and every other treatment, at the 5 percent level. There is no discernible difference between the *H-L* and *L-H* treatments. Finally, the *H-H* treatment has the worst prediction rate of the four, and is significantly below the other three treatments at the 1 percent level, though it is still above the theoretical no-communication prediction (at the 5 percent level).[47]

The data has the aggregate welfare order $\bar{\succ}$:

$$L\text{-}L \,\bar{\succ}^{**} H\text{-}L \,\bar{\succ}^{**} \text{No Communication} \,\bar{\sim}\, L\text{-}H \,\bar{\succ}^{**} H\text{-}H.$$

Where the three stars above the binary relation denote statistical significance at the 1 percent level.[48]

Comparing tables 1 and 2, we observe that subjects only perform better than the equilibrium in the *H-L* environment, where the greater number of sent messages improves prediction outcomes significantly. This requires a costly sacrifice by those with information, a de facto transfer of utility from the informed to the uninformed. So the outcome here is closer to the planner's solution, though welfare is still significantly lower than the optimal level.

The *L-L* treatment fails to live up to the promise of its high-efficiency due to a combination of under-communication and under-attribution, where both $\bar{\Upsilon}$ and $\bar{\Upsilon} - \bar{C}$ are lower than the

[46] These figures are out of 200 points, ignoring the additional 50 fixed endowment, and therefore mirror the utility formulation in Equation (**??**). $\overline{\mathrm{P}}$ is recovered by regressing the total number of earned points divided by 200 on an orthogonal set of treatment dummies, while $\overline{\mathrm{P}} - \overline{c}$ from regressing the earned points net costs divided by 200.

[47] As a proxy for the *No Communication* equilibrium we can look at choices in the experiment with no realized messages. The experimental prediction rate is 62.3 percent across 2,838 subject-rounds.

[48] These significant differences hold when assessed on the entire sample, or just the last ten rounds. These test also hold at the same significance level for a test of first-order stochastic dominance test (see Barrett and Donald, 2003)

equilibrium values. The same is true in the *L-H* treatment, though the ascribed communication failure is only in the under-provision of messages, as the subjects actually listen too often. Finally, the *H-H* treatment exhibits lower welfare than the individually rational point, and subjects would be better off not communicating at all. Because of the excess communication there is a gain in terms of their gross prediction outcomes over *No Communication*, but the costs incurred are too great for there to be net benefits.

***Result 5*:** Aggregate welfare:

- Higher costs for each communication channel are detrimental to welfare.
- A behavioral tendency to over-send information is only beneficial when there are high costs for sending, and when listening is cheap.
- Despite over-communication, subjects fare worse than the equilibrium predictions, except when listening is cheap, and sending expensive.
- When both communication costs are high the presence of a cooperative communication channel reduces welfare.

Similar to the subject-level distributions for the communication cutoffs, Figure 4 illustrates the average outcome by subject across the the experiment. For each subject I compute their average payoff efficiency, $\bar{\Upsilon}_i - \bar{C}_i$, and graph the CDF of subject averages. I also included the theoretical distributions under *No Communication* and the zero-cost planner's solution (the two smooth distributions).[49]

The *L-L* results are unsurprisingly superior to *H-H* in terms of stochastic dominance. But the more surprising results relate to comparisons between *H-L* and *L-H* and between each distribution and the lower bound, *No Communication.* The equilibrium prediction that *L-H*$\overset{\star}{\succ}$*H-L* is reversed, where we find the opposite stochastic relationship, that *H-L*$\bar{\succ}^{\star\star}$*L-H*. Communication in the *H-L* setting does improve outcomes, but the *L-H* distribution is almost coincident with the *No Communication* baseline. The superior behavioral response in *H-L* comes from greater upside to over-sending with high send costs.[50] Over-sending helps move the outcome closer to the planner's prediction, with information much more likely to be provided. Additionally, multiple messages are likely to occur, which helps mitigate under-attribution and better aggregate private information.

Though subjects listen too much in the *L-H* treatment, messages are under-provided, despite being fairly cheap. Equilibrium in this environment is not so inefficient relative to the planner's solution. The combination of under-provision and under-attribution subsequently leads to dissipation of most of the communication gains from over-listening.

---

[49]This provides the distribution for a 30-round average outcome in group of 5. If we took the average over a larger number of rounds these distributions would tend to a point masses at 0 and 100 percent payoff efficiency.

[50]See the difference between $\Upsilon^\star - C^\star$ and $\tilde{\Upsilon} - \tilde{C}$ in Table 1.

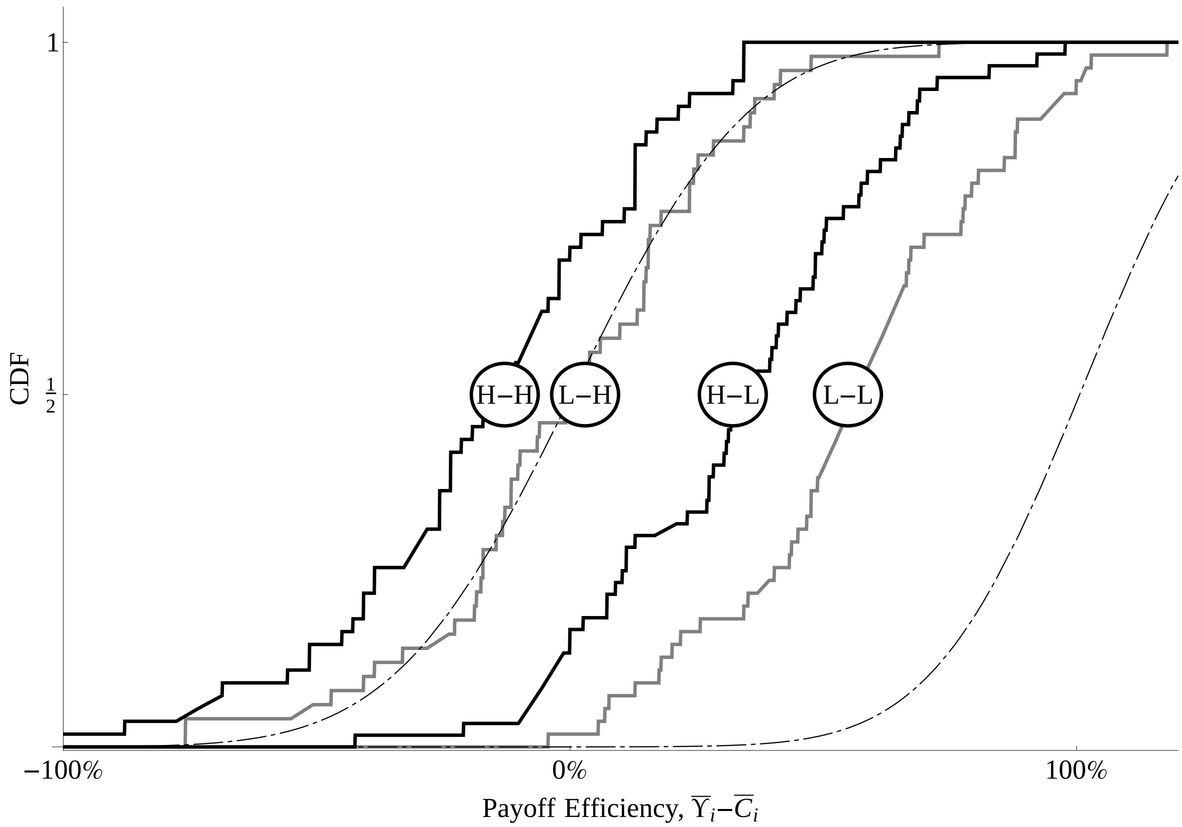


FIGURE 4. Payoff Efficiency, by subject

Because subjects under-interpret the information contained in the received messages they more often pay acquisition costs, but fail to change their final actions when they should. Those with marginal information incur the costs of listening, but requiring more than one message to make a change to their final choices. Outcomes are significantly below the equilibrium prediction: so the extra listening is welfare reducing. This effect becomes more noticeable in the *H-H* treatment, as the number of provided messages becomes even smaller.

Examining the average payoffs in the last 10 rounds of the experiment, 44 percent of subjects in the *L-H* treatment incur lower average payoffs than the no-communication average, while this number increases to 65 percent of subjects in the *H-H* treatments (these numbers are 9 and 17 percent respectively for *L-L* and *H-L*), with the *H-H* distribution stochastically dominated by *No Communication*.

Given Proposition 3 and the fact that the planner's solution is attainable, the experiment can provide us with behavioral evidence for whether subsidizing communication is useful. That is, we can use the realized data from the *L-L* treatment to examine whether subsidies to the communication channel might improve outcomes. For each treatment *H-L*, *L-H* and *H-H*, the theory can predict the expected payoff efficiency if we were to subsidize communication, so that the individuals effective costs were both *Low*. Theoretically, the efficiency gains from making this subsidy are close to the optimal level, with large payoff efficiency increases of 26.5 and 46.8 percent in the *H-H* and *H-L* treatments over the equilibrium level, and a smaller gain of 8.4 percent in the *L-H* treatment.[51]

Looking at the average prediction efficiencies $\bar{\Upsilon}$ in Table 2, the observed prediction gain from changing the cost environment to *L-L* would be 57 percent from *H-H*, 26 percent from *L-H*, and 18 percent from *H-L*. But, once we factor in the cost of the subsidy, and account for the incurred communication costs a less rosy picture emerges. Going from either *H-H* or *L-H* to the *L-L* environment through a subsidy would lead to efficiency decreases, with the payoff efficiency falling by 2.8 percent if moving from *H-H*, and by 20.1 percent if moving from *L-H*. Only in the *H-L* treatment is there a gain, with a 3.8 percent increase in payoff efficiency (far less than the 46.8 percent possible).

These results should make us wary when considering subsidies for information transfer. Observed behavior in the experiment indicates excessive provision and acquisition when the costs are *High*. Excessive provision is socially useful, as free-riding on others' provision is more problematic in larger groups (particularly given under-attribution by those listening). Subsidizing the send costs does lead to some small welfare gains, though not as much as predicted. Excessive acquisition, though it *could* lead to gains, actually produces net welfare losses. Group members acquire information frequently, even when they have good private information. However, the acquired information is utilized too little in their final choice. The subsidy's benefit is subsequently dissipated while the costs are fully borne.

5. CONCLUSION

I develop a simple model in which to analyze communication frictions within aligned-interest groups—detailing how costs faced by individuals leads to sub-optimal exchange of information. Taking my theory to the laboratory I analyze how human subjects react to changes in the costs/benefits of providing and consuming information within the group. Using the theoretical model as both a benchmark for comparison, and to provide a structured lens through which to view the results, I find many points of agreement with the theory but also some large departures.

My theoretical predictions correctly order the listening and sending behavior, with subjects broadly following the comparative-static predictions. Examining the results at the subject level, I find clear stochastic relationships between treatments. However, a large departure from the homogenous predictions of the theory is the heterogeneous response by

[51]Per Table 1, optimal subsidies would produce payoff efficiency gains of 27.1%, 47.3% and 12.1%, respectively.

subject. Previous experimental work has mostly focused on information transmission in environments where senders and receivers have misaligned preferences, but has documented similar heterogeneity. A common explanation is variance in strategic sophistication. When preferences are aligned, but we allow for frictions, explanations through heterogeneity in strategic thinking are insufficient. My results instead indicate that descriptive explanations for over-communication might better focus on variation in preferences for information exchange/honesty, rather than a variation in strategic thinking.

Subjects in my experiment under-communicate when communication costs are small, providing too little information to others, and listening too infrequently. This effect is primarily driven by sub-optimal updating rules used by subjects. When either communication cost is high and the first-best outcome is further from the equilibrium level, subjects share more information than predicted, improving the collective choice, but simultaneously incurring large costs. Over-communication is socially beneficial only when the costs for sending messages are high and listening is cheap—the gain from over-provision outweighs the additional costs. In all other treatments the subjects' final outcomes are below the sub-optimal equilibrium level. Interestingly, when both costs are high subjects' outcomes are dominated by those they would obtain from entirely disengaging from all communication.

In terms of policy, consider a planner in an environment with high communication frictions, debating which channel to subsidize. For instance, suppose we have excess funds for a seminar: should we pay an honorarium to the speaker or spread this same amount among the audience for attending? The experimental results indicate that subsidies to those acquiring information lead to the greatest gains in information transmission. Whatever the form of this subsidy—giving a free sandwich to audience members in a seminar, paying referees at a journal, increasing the attendance payments for directors on a boards—my experimental results indicate that loss of audience seems to be the more pernicious effect on aggregation. However, my results also suggest that listening subsidies end up being fairly wasteful, once we weigh the information gains against the opportunity costs of the subsidy. When communication costs are very large, social planners must also consider, behaviorally at least, that they might increase total welfare by *removing* the communication channel entirely.

REFERENCES

AUSTEN-SMITH, D., AND T. J. FEDDERSEN (2005): "Deliberation and Voting Rules," in *Social Choice and Strategic Decisions: Essays in Honor of Jeffrey S. Banks*, ed. by D. Austen-Smith, and J. Duggan. Springer.

BANERJEE, A., AND R. SOMANATHAN (2001): "A Simple Model of Voice," *Quarterly Journal of Economics*, 116(1), 189–227.

BARRETT, G. F., AND S. G. DONALD (2003): “Consistent tests for stochastic dominance,” *Econometrica*, 71(1), 71–104.

BATTAGLINI, M., AND U. MAKAROV (2011): “Cheap Talk with Multiple Audiences: an Experimental Analysis,” mimeo, Princeton University.

BLINDER, A., AND J. MORGAN (2005): “Are two heads better than one? Monetary policy by committee,” *Journal of Money, Credit and Banking*, pp. 789–811.

BLUME, A., P. KRISS, AND R. WEBER (2012a): “Organizational Coordination with Decentralized Costly Communication,” working paper, University of Pittsburgh.

——— (2012b): “Pre-Play Communication with Forgone Costly Messages: Experimental Evidence on Forward Induction,” working paper, University of Pittsburgh.

BRANDTS, J., AND G. CHARNESS (2000): “Hot vs. cold: Sequential responses and preference stability in experimental games,” *Experimental Economics*, 2(3), 227–238.

——— (2009): “The strategy method: A survey of experimental evidence,” Discussion paper, Department of Business Economics U. Autònoma de Barcelona.

CAI, H., AND J. T.-Y. WANG (2006): “Overcommunication in strategic information transmission games,” *Games and Economic Behavior*, 56(1), 7–36.

CALVÓ-ARMENGOL, A., J. DE MARTÍ, AND A. PRAT (2011): “Communication and Influence,” working paper, London School of Economics.

CHEN, Y. (2011): “Perturbed communication games with honest senders and naive receivers,” *Journal of Economic Theory*, 146(2), 401–424.

CHEN, Y., N. KARTIK, AND J. SOBEL (2008): “Selecting Cheap-Talk Equilibria,” *Econometrica*, 76(1), 117–136.

CHUNG, W., AND R. HARBAUGH (2012): “Biased Recommendations,” mimeo, Indiana University.

COOPER, D., AND J. KAGEL (2005): “Are two heads better than one? Team versus individual play in signaling games,” *American Economic Review*, pp. 477–509.

CRAWFORD, V. P., AND N. IRIBERRI (2007): “Level-k Auctions: Can a Nonequilibrium Model of Strategic Thinking Explain the Winner’s Curse and Overbidding in Private-Value Auctions?,” *Econometrica*, 75(6), 1721–1770.

CRAWFORD, V. P., AND J. SOBEL (1982): “Strategic Information Transmission,” *Econometrica*, 50(6), 1431–1451.

DESSEIN, W., AND T. SANTOS (2006): “Adaptive organizations,” *Journal of Political Economy*, 114(5), 956–995.

DEWATRIPONT, M., AND J. TIROLE (2005): “Modes of Communication,” *Journal of Political Economy*, 113(6), 1217–1238.

DICKHAUT, J. W., K. A. MCCABE, AND A. MUKHERJI (1995): "An experimental study of strategic information transmission," *Economic Theory*, 6, 389–403, 10.1007/BF01211783.

FEDDERSEN, T., S. GAILMARD, AND A. SANDRONI (2009): "Moral bias in large elections: theory and experimental evidence," *American Political Science Review*, 103(2), 175–192.

FISCHBACHER, U. (2007): "z-Tree: Zurich toolbox for ready-made economic experiments," *Experimental Economics*, 10(2), 171–178.

GNEEZY, U. (2005): "Deception: The Role of Consequences," *American Economic Review*, 95(1), 384–394.

KARTIK, N. (2009): "Strategic communication with lying costs," *The Review of Economic Studies*, 76(4), 1359–1395.

LAI, E. K., W. LIM, AND J. T.-Y. WANG (2011): "Experimental Implementations and Robustness of Fully Revealing Equilibria in Multidimensional Cheap Talk," mimeo, National Taiwan University.

MCCUBBINS, M. D., AND D. B. RODRIGUEZ (2006): "When Does Deliberating Improve Decisionmaking?," *Journal of Contemporary Legal Issues*, 15.

NAGEL, R. (1995): "Unraveling in Guessing Games: An Experimental Study," *American Economic Review*, 85(5), 1313–26.

NYARKO, Y., AND A. SCHOTTER (2002): "An experimental study of belief learning using elicited beliefs," *Econometrica*, 70(3), 971–1005.

OLSZEWSKI, W. (2004): "Informal communication," *Journal of Economic Theory*, 117(2), 180–200.

OSBORNE, M. J., J. S. ROSENTHAL, AND M. A. TURNER (2000): "Meetings with Costly Participation," *American Economic Review*, 90(4), 927–943.

PALFREY, T. R. (In preparation): "Political Economy," in *The Handbook of Experimental Economics, Volume 2*, ed. by J. H. Kagel, and A. E. Roth.

ROTH, A., AND M. MALOUF (1979): "Game-theoretic models and the role of information in bargaining," *Psychological review*, 86(6), 574–594.

SMORODINSKY, R., AND M. TENNENHOLTZ (2006): "Overcoming free riding in multiparty computations—The anonymous case," *Games and Economic Behavior*, 55(2), 385–406.

STAHL, D. O., AND P. W. WILSON (1994): "Experimental evidence on players' models of other players," *Journal of Economic Behavior & Organization*, 25(3), 309–327.

——— (1995): "On Players' Models of Other Players: Theory and Experimental Evidence," *Games and Economic Behavior*, 10(1), 218–254.

TAYLOR, C. R., AND H. YILDIRIM (2010): "A unified analysis of rational voting with private values and group-specific costs," *Games and Economic Behavior*, 70(2), 457–471.

VESPA, E., AND A. J. WILSON (2014): "Communication with Multiple Senders: An Experiment," mimeo, University of Pittsburgh.

WANG, J., M. SPEZIO, AND C. F. CAMERER (2010): "Pinocchio's Pupil: Using Eyetracking and Pupil Dilation to Understand Truth Telling and Deception in Sender-Receiver Games," *American Economic Review*, 100(3), 984–1007.

APPENDIX A. PROOFS

Proposition 1. Given a belief that the other $n-1$ agents use symmetric strategies μ and ρ, agent i of information type $x_i \geq \frac{1}{2}$, who is otherwise leaning towards choosing option A, seeks to maximize the expected outcome.[52] The listening decision of i can not affect the choices of others, y_{-i}, and the message decision m_i does not affect agent i's final decision y_i. The two decisions are additively separable so we can maximize each independently.

Taking the listening decision first. The agents choose to listen when the likely benefit to their own decision of additional information outweighs the costs.[53] There is a $(1-x_i)$ chance the agent makes an incorrect decision without additional information, incorrectly choosing A over B. The *benefit* of listening is therefore α utils multiplied by the chance the agent is misinformed, $(1-x_i)$ multiplied by the probability that others provide corrective information leading to the final decision B. With some probability, the provided messages could lead to an incorrect decision, so the *total cost* of listening is the potential loss from switching to an incorrect decision based on observed messages and the sunk cost of listening. So an agent of type x_i listens whenever

$$\alpha \cdot (1-x_i) \cdot \Pr\left\{\lambda(x_i, \mu(x_{-i})) < 1/2 \,|x_i, B\right\} > \alpha \cdot x_i \cdot \Pr\left\{\lambda(x_i, \mu(x_{-i})) < 1/2 \,|x_i, A\right\} + c_R.$$

Showing that the optimal strategy is a cutoff requires us to show that the LHS shrinks faster than the RHS as x_i increases. Using the symmetry properties of the signal distributions and the definition of the Bayesian posterior λ this is equivalent to checking the slope of

$$\begin{aligned}
& (1-x_i) \cdot \Pr\left\{\lambda(1-x_i, \mu(x_{-i})) > 1/2 \,|x_i, A\right\} - x_i \cdot \Pr\left\{\lambda(x_i, \mu(x_{-i})) < 1/2 \,|x_i, A\right\} \quad , \\
= \; & (1-x_i) \cdot \Pr\left\{x_i < \lambda\left(1/2, \mu\left(x_{-i}\right)\right) |x_i, A\right\} - x_i \cdot \Pr\left\{x_i < \lambda\left(1/2, \mu\left(1-x_{-i}\right)\right) |x_i, A\right\} \quad , \\
= \; & \int\!\cdots\!\int \left[(1-x_i) \cdot \mathbf{1}\left\{x_i < \lambda\left(1/2, \mu\left(\mathbf{x}_{-i}\right)\right)\right\} - x_i \cdot \mathbf{1}\left\{x_i < \lambda\left(1/2, \mu\left(1-\mathbf{x}_{-i}\right)\right)\right\}\right] dF_A(\mathbf{x}_{-i}) \quad , \\
= \; & (1-x_i) \int\!\cdots\!\int \left[1 - \tfrac{x_i}{1-x_i} \cdot \prod_{j \neq i} \tfrac{1-x_j}{x_j}\right] \cdot \mathbf{1}\left\{x_i < \lambda\left(1/2, \mu\left(\mathbf{x}_{-i}\right)\right)\right\} dF_A(\mathbf{x}_{-i}).
\end{aligned}$$

This is decreasing in x_i (strictly if there exists a plausible $(n-1)$-tuple of messages that could make type x_i change their decision). The optimal strategy is therefore always characterized

[52] A symmetric argument deals with the case when $x_i \leq \frac{1}{2}$ and the agent is predisposed to choose *B*.

[53] For tractability the following ignores the possibility of indifference.

by a cutoff $r(\mu) \geq \frac{1}{2}$ at the point of indifference, which, given the effective cost $\frac{c_L}{\alpha}$ solves:

$$r(\mu) = \max\left\{{}^1\!/\!{}_2, \frac{\Pr\left\{\lambda(1-r(\mu),\mu(x_{-i})) > {}^1\!/\!{}_2\,|A\right\} - {}^{c_R}\!/\!{}_\alpha}{\Pr\left\{\lambda(1-r(\mu),\mu(x_{-i})) > {}^1\!/\!{}_2\,|A\right\} + \Pr\left\{\lambda(r(\mu),\mu(x_{-i})) < {}^1\!/\!{}_2\,|x_i, A\right\}}\right\}.$$

The sending logic is similar, though we require the fact that others' listening strategies have the cutoff form. The agent must ask which message is most effective to convince a representative other group member $j \in \mathcal{I}$, given the fixed message behavior of the $n-2$ agents in $\mathcal{I} \setminus \{i, j\}$. An agent of type $x_i > \frac{1}{2}$ prefers sending a costly message m to the empty message $m_\emptyset$ ($m \succ_{x_i} m_\emptyset$) when the gain from convincing those types of j who would otherwise choose incorrectly outweighs the fixed cost of sending, and the possibility they misinform.

Fixing the listening strategy, ρ_j, define the set of listening types as $L(\rho_j) := \{x \in X\,|\rho_j(x) = \text{Listen}\}$, and the set of types strictly preferring A after observing the messages $\mathbf{m}_{-j}$ as $T_\mu(\mathbf{m}_{-j}) := \{x_j \in X\,|\lambda(x_j, \mathbf{m}_{-j}) > {}^1\!/\!{}_2\}$. Define the probability of the event that, given a message m from player i, group member j chooses correctly conditional on $\omega = A$ as

$$\Pi(m;\mu,\rho,\nu) \;=\; \Pr\left\{x_j \in T_\mu\left(\mu(\mathbf{x}_{-i,j}), m\right) \cap L(\rho_j)\,|\omega = A\right\}.$$

So $\Pi(m;\mu,\rho,\nu)$ represents the probability the agent chooses A factoring in both the listening behavior (ρ_j), the beliefs about about how others interpret message content (ν), and the sending behavior of others (μ).[54] The agent prefers to send the message m when

$$x_i \cdot \Pi(m) + (1-x_i)\cdot\Pi(-m) \quad - \frac{c_M}{(1-\alpha)} \quad > \Pi(m_\emptyset), \tag{13}$$

where we denote $-m$ as the complementary message to m, (i.e. $\nu(-m) = 1-\nu(m)$).

We want to show that $m \succ_{x_i} m_\emptyset \Rightarrow m \succ_{x_i'} m_\emptyset$ for all $x_i' > x_i$. We therefore require

$$\Pi(m) - \Pi(-m) > 0,$$

which is true so long as the message m carries information that increases the probability of A being selected ($\nu(m) > \frac{1}{2}$) and there exists some type that will be swayed by the message (i.e. $T_\mu\left(\mu(\mathbf{x}_{-i,j}), m\right) \cap L(\rho_j)$ is not empty).

From (13) an agent is indifferent between a message m and the empty message $m_\emptyset$ at the point $x_{m,m_\emptyset}$ given by

$$x_{m,m_\emptyset} = \min\left\{1, \frac{\Pi(m_\emptyset) - \Pi(-m) + {}^{c_M}\!/\!{}_{1-\alpha}}{\Pi(m) - \Pi(-m)}\right\}.$$

The final part of the characterization, generalizes the model to richer message spaces, and relates to the ranking of potential costly messages. An agent of type $x_i > \frac{1}{2}$ prefers one

[54]For clarity I suppress the explicit dependence on μ, ρ and ν from here on.

message m to another message m' ($m \succ_{x_i} m'$) if

$$x_i\left[\Pi(m)-\Pi(m')\right] \quad > \quad (1-x_i)\left[\Pi(-m')-\Pi(-m)\right].$$

If the messages are ordered so that $\nu(m)>\nu(m')$ this implies $\Pi(m)-\Pi(m')\geq 0$, so there exists a critical type $x_{m,m'}$ such that

$$x_{m,m'}=\frac{\Pi(-m')-\Pi(-m)}{\Pi(m)-\Pi(m')+\Pi(-m')-\Pi(-m)}, \tag{14}$$

with the property that $m\succ_x m'$ for all types $x>x_{m,m'}$, and $m'\succ_x m$ for all $x<x_{m,m'}$. The optimal message best response is therefore constructed according to:

$$q(x_i;\mu,\rho):=\arg\max_{\succ_{x_i}} M.$$

For any message space M, in a neighborhood of $x=\frac{1}{2}$ the best message is always $m_\emptyset$ whenever the effective listening cost $\frac{c_M}{1-\alpha}>0$.

Every symmetric equilibrium strategy (μ,ρ) is a fixed point of the best-response map (where the belief ν of other agents is pinned down in equilibrium via μ)

$$BR\begin{pmatrix}\mu(\cdot)\\ \rho(\cdot)\end{pmatrix}=\begin{pmatrix}q(\cdot;\mu,\rho)\\ r(\cdot;\mu)\end{pmatrix}.$$

Because BR maps every communication strategy into the above cutoff-form, every fixed point of BR must also have the above cutoff form. □

Proposition 3. Define the most-sending informative equilibrium solution with arbitrary positive costs c_M and c_R

$$\theta^\star(c_M,c_R):=\inf\left\{\theta\,|\theta=q_R(\theta;c_M,c_R)=q\left(\theta,r\left(\theta;c_R\right);c_M\right)\right\}.$$

The equilibrium solution is weakly increasing in both costs (strictly for informative solutions), as the curve $q_R(\theta;c_M,c_R)$ shifts upward smoothly in both costs, indicating reduced sending behavior from decreasing benefits to informing others ($q(\theta,\rho)$ increases if ρ decreases, while $r(\theta;c_R)$ is decreasing in c_R) and increasing send costs. Because the curve shifts upward in both costs and the first crossing of the 45-degree line is from above (q_R continuous, and $q_R(\frac{1}{2})>\frac{1}{2}$ whenever $c_M>0$) the fixed point $\theta^\star(c_M,c_R)$ is increasing in both costs.

I will show that the solution of the planner's problem is given by $\tilde{\theta}=\theta^\star\left(\frac{(1-\alpha)}{n-1}\cdot c_M,\alpha\cdot c_R\right)$. First, an individual at listening cost $\alpha\cdot c_R$ with accurate beliefs about others' send cutoffs makes the same decision as a planner would facing cost c_R for all possible cutoffs θ, so the planner's listening policy is simply $r_\alpha(\theta) := r(\theta; \alpha \cdot c_R)$. The planner's symmetric cutoff problem can be written as the solution to

$$\max_\theta P(\theta, \ldots, \theta, r_\alpha(\theta)) - [1 - F(\theta) + F(1-\theta)]\, c_M - [F(r_\alpha(\theta)) - F(1 - r_\alpha(\theta))]\, c_R,$$

where $P(\theta_1, \ldots \theta_{n-1}, \rho)$ is the ex ante prediction rate for an agent with listening cutoff ρ receiving messages from the $n-1$ other group-members, using the cutoffs $\theta_1, \ldots, \theta_{n-1}$. Given the symmetry of P in the first $n-1$ arguments, a necessary condition for an interior planner's solution is that

$$(n-1)P_1\left(\tilde{\theta}, \ldots, \tilde{\theta}, r_\alpha(\tilde{\theta})\right) + P_n\left(\tilde{\theta}, \ldots, \tilde{\theta}, r_\alpha(\tilde{\theta})\right) \left.\frac{\partial r_\alpha(\theta)}{\partial \theta}\right|_{\tilde{\theta}} = \frac{f(\theta)}{\theta} c_M + \frac{f\left(r_\alpha(\tilde{\theta})\right)}{r_\alpha(\tilde{\theta})} c_R \left.\frac{\partial r_\alpha(\theta)}{\partial \theta}\right|_{\tilde{\theta}},$$

where the RHS uses the identity that $\frac{f(x)}{f(1-x)} = \frac{x}{1-x}$ for any reduced form signal distribution.

The individual's decision at the equilibrium $\hat{\theta} = \theta^\star(\hat{c}_M, \hat{c}_R)$ is found by solving

$$\max_{q,r} (1-\alpha) \cdot P\left(q, \hat{\theta}, \ldots, \hat{\theta}, r_\alpha(\hat{\theta})\right) + \alpha P\left(\hat{\theta}, \hat{\theta}, \ldots, \hat{\theta}, r\right) - \\ [1 - F(q) + F(1-q)]\, \hat{c}_M + [F(r) + F(1-r)]\, \hat{c}_R.$$

Necessary condition for best response at this point are therefore that

$$P_1\left(\hat{\theta}, \hat{\theta}, \ldots, \hat{\theta}, r_\alpha(\hat{\theta})\right) = -\frac{f(\theta)}{\theta} \cdot \frac{\hat{c}_M}{(1-\alpha)}$$

and

$$P_n\left(\tilde{\theta}, \ldots, \tilde{\theta}, r_\alpha(\tilde{\theta})\right) = -\frac{f\left(r_\alpha(\tilde{\theta})\right)}{r_\alpha(\tilde{\theta})} \cdot \frac{\hat{c}_R}{\alpha}.$$

It is then fairly trivial to show that planner's FOC is satisfied at the equilibrium point $\theta^\star\left(\frac{(1-\alpha)}{n-1} \cdot c_M, \alpha \cdot c_R\right)$. A second-order condition on the planner's solution follows fairly easily by continuing the construction in the cost-space (c_M, c_R) through $\theta^\star(c_M, c_R)$. □

APPENDIX B. ADDITIONAL ANALYSES

B.1. **Dynamics.** Table 4a presents regression results by treatment for changes in the listen cutoff, $\Delta\rho_{it} = \rho_{it} - \rho_{it-1}$. The first regressor is the benefit, *Listen; true*, a dummy indicating whether the subject's cutoffs in the previous round led them to listen **and** that they received messages for the *ex post* correct state. Cutoffs move insignificantly in reaction to receiving good information in the previous round. However, when subjects listened and observed no messages in the previous round (*Listen; no message*) the reduction in the cutoff is large and significant, with an approximate decrease of 0.035 in the listening cutoff. *Listen; false* is a dummy indicating bad information, that the subject received excess messages for the *ex post*

TABLE 4. Learning

(A) Change in Listen Cutoff, $\Delta\rho$

Variable$_{t-1}$	***L-L***	***H-L***	***L-H***	***H-H***
Listen; true	0.005	-0.006	-0.010	0.002
	(0.007)	(0.006)	(0.007)	(0.007)
Listen; no message	-0.039***	-0.038***	-0.037***	-0.032***
	(0.009)	(0.006)	(0.010)	(0.008)
Listen; false	0.001	-0.026**	-0.026**	-0.022*
	(0.012)	(0.012)	(0.011)	(0.012)
Not Listen; no message	-0.049***	-0.055***	-0.049***	-0.017*
	(0.012)	(0.008)	(0.012)	(0.010)
Trend	0.011**	0.016***	0.012***	0.006
	(0.005)	(0.003)	(0.004)	(0.004)

(B) Send Cutoff Changes, $\Delta\theta$

Variable$_{t-1}$	***L-L***	***H-L***	***L-H***	***H-H***
Sent true	0.039***	0.050***	0.031***	0.04.0***
	(0.006)	(0.006)	(0.007)	(0.007)
Sent false	0.058***	0.083***	0.064***	0.041**
	(0.013)	(0.014)	(0.014)	(0.014)
No listeners	-0.008	0.020*	0.024**	0.012
	(0.030)	(0.012)	(0.010)	(0.010)
Many messages	0.010	-0.010	-0.003	-0.002
	(0.006)	(0.008)	(0.007)	(0.008)
Trend	-0.010***	-0.007***	-0.009***	-0.005
	(0.003)	(0.002)	(0.003)	(0.002)

Note: All estimates are assessed using a fixed-effects regression model with the dependent variables $\Delta\rho_{it} = \rho_{it} - \rho_{it-1}$ and $\Delta\theta_{it} = \theta_{it} - \theta_{it-1}$, respectively; standard errors in parentheses. Significance stars: 10 percent–*; 5 percent–**; 1 percent–***.

incorrect state. Here there is an approximate 0.025 drop in listening cutoffs following this event.[55] Subjects seem to be more reactive to a *lack* of information provision, rather than the information proving false. Additionally, there is an even larger reduction in the subsequent listening cutoffs if in the previous round there were no messages sent *and* the subject did not listen (*Not listen; no message*, where this information was available to subjects in the round feedback). Finally the *Trend* provides a constant term, indicating the general trend was for subjects to increase their listening as the sessions went on.

Table 4b presents similarly motivated regressions for the changes in send cutoff, $\Delta\theta_{it} = \theta_{it} - \theta_{it-1}$. First, there does seem to be a strong reaction to incurring costs, either implicit and explicit. Sending a correct message in the previous round (*Sent true*) is associated with a reduction in provision, with a 0.03–0.05 increase in the send cutoff used. The reduction in provision is much larger if the message sent was incorrect (*Sent false*), so there is a strong reaction to misinforming others.[56] In terms of the listening behavior, send cutoffs do respond to a lack of listeners in the previous period (*No listeners*), but this effect is only significant in the *H-L* and *L-H* treatments. Finally, the theory makes clear that the incentives to send decrease as others provide more, but subjects do not react if the previous round had more than two excess correct messages (*Many messages*, which occurs in approximately 10 percent of rounds across treatments).[57] Subjects do not react to pivotality in a dynamic sense, which is related to similar results in experiments on turnout in elections.[58]

B.2. **Preference Rationalization.** Given the realized data, we might seek to rationalize the observed play by the preferences of subjects. In order to do this I will assume that agents have heterogeneous costs/benefits. Suppose that agents derive a benefit for choosing the correct state themselves given by $\alpha_{\text{Self}} > 0$, and derive a benefit from others choosing the correct state given by $\alpha_{\text{Other}s}$. Similarly, the subject has some personal cost of providing information given by $\bar{C}^i_M(c_M)$ and some individual cost of listening given by $\bar{C}^i_R(c_R)$.[59]

---

[55]This event happens fairly infrequently in the data (about 5–10 percent of the time, conditional on listening, compared to a 39–55 frequency for listening with no message).

[56]This event is fairly rare in the data, and is unsurprisingly highly correlated with the subject using a very low send cutoff.

[57]Similarly, inclusion of an indicator variable representing cases when no messages were supplied in the previous period (so the oppositely motivated regressor) is also insignificant.

[58]See for instance Feddersen, Gailmard, and Sandroni (2009) or for more experimental references see Palfrey (In preparation).

[59]Note that this is in contrast with the induced experimental benefits of $\alpha_{\text{Self}} = \alpha_{\text{Others}} = 100$, and the experimentally induced costs of $c_M, c_R \in \{5, 25\}$ .The induced cost/benefit ratios are therefore either 5 or 25 percent. Costs are exogenously shifted by the experimental environment, so implied cost distributions are a function of the experimentally induced cost.

For any observation I can invert the theoretical best-response maps given in (5) and (6) to recover an implied cost/benefit ratio pair (henceforth just "the implied cost") that rationalizes the data: $\vec{c}^{\,i}_M(c_M) = \bar{C}^i_M(c_M)/\alpha^i_{\text{Others}}$ for sending, and $\vec{c}^{\,i}_R(c_R) = \bar{C}^i_R(c_R)/\alpha^i_{\text{Self}}$ for listening. To do this I will assume the structure of the model, so that subjects are best-responding to the aggregate parameters assessed in Table (2). However, to adjust for the estimated non-Bayesian updating behavior, I will use an updating rule where the message content is given a fixed information content across treatments, equivalent to using $\xi(\eta) = 72\%$ (see the values assessed in Table 3).[60]

Using the average cutoffs $\bar{\theta}_i$ and $\bar{\rho}_i$ specified over the last 10 rounds by each subject i, and taking the behavior of others as given by the treatment averages from Table 2, I calculate the implied cost/benefit ratios $\vec{c}^{\,i}_M(c_M)$ and $\vec{c}^{\,i}_R(c_R)$ by subject. When subjects specify cutoffs at a boundary the implied cost is censored. So for a subject that specifies never to listen in any of the last 10 rounds, I only obtain an upper bound on the implied listening cost. Similarly, were they to specify to always listen, I would recover a lower bound on the listening cost of zero.

Using a bi-variate Tobit model I estimate four population averages: the implied send and listen costs under the treatment costs of *High* and *Low*. Additionally, I simultaneously estimate the population standard-deviations for each implied cost, and the correlation between the two implied costs.[61] The estimated parameters are listed in Table (5).

This exercise is descriptive. However, if we believe the benefits were as induced, because of the exogenous variation of the costs, we can specify the tests that $\mu_M(\boldsymbol{H}) - \mu_M(\boldsymbol{L}) = 20\%$ and $\mu_R(\boldsymbol{H}) - \mu_R(\boldsymbol{L}) = 20\%$, the exogenously induced cost difference in the experiments. However, as the Table makes clear, the induced difference in costs is much smaller: approximately 6 percent for sending and just 3 percent for listening. So either subjects heavily underweight the induced costs, or they derive a larger than induced benefits in the task. With these implications being stronger for their own choices than for others (for instance, with $\alpha_{\text{Self}} > \alpha_{\text{Others}}$).

The positive correlation implies that those who derive some additional pleasure from sending message, also derive more utility from listening. Those who disengage from seeking out information from others are also less likely to be contributors.

[60]This accounts for the assessed departure from Bayesian updating discussed in section 4.2, so that we are backing out preference parameters over communication only. The main effect of non-Bayesian updating is to lower the implied listening costs by approximately 0.05.

[61]Costs are assumed to be distributed as

$$\begin{pmatrix} c^i_M \\ c^i_R \end{pmatrix} \sim \mathcal{N}\left[\begin{pmatrix} \mu_M(c_M) \\ \mu_R(c_R) \end{pmatrix}, \begin{pmatrix} \sigma^2_M & \varrho\sigma_M\sigma_R \\ \varrho\sigma_M\sigma_R & \sigma^2_R \end{pmatrix}\right]$$

where the mean costs μ_M and μ_R are conditional on either *High* or *Low* values for the experimental costs c_M and c_R, respectively.

TABLE 5. Implied-Cost Distribution Averages

Implies Costs	***Sending,*** μ_M	***Listening,*** μ_L
High experiment cost, $\mu(H)$, $c = 25\%$	14.2%	8.7%
	(0.7)	(0.6)
Low Experiment cost, $\mu(L)$, $c = 5\%$	7.9%	5.7%
	(0.7)	(0.6)
Std. Dev.	7.7%	6.2%
	(0.4)	(0.3)
Correlation	0.27	
	(0.06)	
N_S	220	

Note: All estimates are assessed using a bi-variate Tobit-type estimator where the dependent variable is the implied cost-pair by subject; coefficients report the mean, std. deviation and correlation between costs; standard errors for all estimated parameters are in parentheses..

My point in this section is not to use this revealed-preference approach to explain the data or human behavior of this type definitively, but to point out the necessary steps for rationalizing the observed data, and what the subsequent implications are on the underlying preferences.

APPENDIX C. INSTRUCTIONS

INSTRUCTIONS

Welcome. You are about to participate in an experiment on decision making and you will be paid for your participation with cash vouchers, privately at the end of the session. The money you earn will depend on both your decisions, the decisions of others and chance.

The session will be conducted through your computer terminal, and all communication and interaction between you and the other participants in this session will take place through your screens. Do not talk to or attempt to communicate with other participants during the experiment.

Please make sure to turn off phones and similar devices now.

Please close any applications you have open on your computers.

The session will begin with a brief instructional period, during which you will be informed of the main features of the task, and you will be shown how to use your computers. Please raise your hand if you have any questions during this period and your question will be answered so that everyone can hear.

Summary. Your aim in each round will be to correctly guess the result of a coin flip, and your payoff will depend both on whether you got the correct answer AND on the number of other group members who were correct, in particular, the more members of your group that get the answer correct the greater your likely earnings.

Every member of the group will receive a signal pointing to whether heads or tails occurred, with varying accuracy, and you will be given the opportunity to send messages to each other; however, both deciding to send and/or deciding to listen will be costly.

The session will consist of two sections over which the main task and payoffs will remain the same, however, an additional element will be added in the second part for which there will be an additional payment. The first part will last for 20 rounds, after which you will be given instructions on the second part which will last for a further 10 rounds.

Steps. Your task in each of the 30 rounds has the following structure:

(1) In each round you will be randomly divided into groups of **5**.
(2) Your ultimate task will be to make a decision as to whether a fair coin, flipped by the computer at the start of the round, landed *HEADS* or *TAILS*. The true outcome of the flip will be kept secret from all subjects until the end of each round.
(3) You will receive a signal of the coin flip which has an "accuracy" between 50–100%. Before receiving this signal you must choose the accuracy level at which you wish

to communicate: this is a cutoff for sending a message $SEND$, and a cutoff for listening to message(s) $LISTEN$.

- If the signal you receive has an accuracy level **higher** than $SEND$ you will automatically **send** a message for the most likely outcome, given your signal, to those listening.
- If the signal accuracy is **lower than or equal to** $SEND$ you will **not send** a message. Entering $SEND$=100 means you will never send messages.
- If the signal you receive has an accuracy level **lower** than $LISTEN$ you will automatically **listen** to any messages sent by other group members.
- If the signal accuracy is **higher than or equal to** $LISTEN$ you will **not listen** to messages. Entering $LISTEN$=50 means you will never listen to messages.
- The cost to send messages will be 25 experimental points, and the cost to listen will be 5 experimental points: If your signal accuracy is higher than $SEND$ you will incur the cost of sending a message. If your accuracy is lower than $LISTEN$ you will incur the same cost for listening to messages, whether you see 0,1,2,3 or 4 messages, 5 points.

(4) After choosing when you will send messages you are given your signal. With probability $\frac{1}{2}$ your signal will be meaningless and will not inform you on the outcome of the coin flip. With probability $\frac{1}{2}$ you will be given a signal with an "accuracy" between 50–100%, which will be described in the **Signals** section below.

(5) Messages are sent according to the cutoffs $SEND$ and $LISTEN$ you specified in step 3.

- N.B. You will **only** incur the costs for sending in a round if your accuracy is greater than your cutoff $SEND$. You will only incur the costs for listening in a round if your accuracy is lower than your cutoff $LISTEN$.

(6) If you end up listening to messages (your accuracy is less than $LISTEN$), you will be given the number of messages for *HEADS* and for *TAILS* sent by the other 4 group members.

- So if you transmitted a message, each of the other group members that choose to listen would see your message.
- If you chose to listen, you would see the number of messages sent by the other 4 group members; if you chose not to listen this information will not be shown.

(7) Finally, each group member chooses their prediction of the coin flip: *HEADS* or *TAILS*. The maximum points you can make in a round is 250 and the minimum is 0. The exact formula for the points you can earn is given in the **Round payoffs** section below.

(8) After you have given your prediction of the coin flip the round-summary screen will let you know the following:
   - The result of the coin flip.
   - Whether you were correct.
   - Your total earnings from this round in experimental points.
   - How many members of your group were correct.
   - The accuracy of each group member's signal and whether they decided to listen and/or send a message.
   - Your personal history from each round.

Round payoffs. Your payoffs in every round will be determined by your decisions and those of the other subjects as described below:

- You begin each round with 50 points.
- If **you** correctly predict the coin flip you will receive 100 points.
- You will also receive 25 points for every **other group member** that chose the correct result—so 100 points if all 4 are correct.
- Any costs for messages you have sent, or for listening will be removed from your total as follows: 25 points will be removed if you chose to send a message, 5 points removed if you chose to listen to others' messages.
- The total possible points in a round is 250 and corresponds to everyone in the group correctly picking the coin flip, and you individually incurring no costs from messages.
- The minimum possible points in a round is 20 and corresponds to everyone in the group incorrectly picking the coin flip, and you personally incurring costs from both sending and listening to messages.

Signals.

- With probability $\frac{1}{2}$ each group member receives a signal of the coin flip:
   (1) If you receive a signal you will be given a random number X between 0 and 100, where the probability of receiving any number is the same.
   (2) The computer draws another number Y, one for each group member, which you will not know, between 0 and 100, using the same method as X.
   (3) If the second number Y is less than or equal to X you will be told the correct outcome of the coin flip. If Y is greater than X you will be told the opposite of the correct flip.
   (4) So, if you receive a signal, you will be told a number X and a potential coin-flip outcome.

- The number X can be interpreted as the percentage chance that you were told the correct outcome.
- A signal ($X\%$,*TAILS*) is equivalent to the signal ($100 - X\%$,*HEADS*). We will call your signal **"accuracy"** the larger number of $X\%$ and $(100 - X)\%$.
- If you got the signal (4.90, *HEADS*) there is a 4.90% chance the outcome is *HEADS* and a 95.10% chance the outcome is *TAILS*, so your **accuracy** is 95.10%. If you receive the signal (59.10, *HEADS*), then there is a 59.10% chance the outcome is *HEADS* and a 40.90% chance of *TAILS*, so your **accuracy** is 59.10%.

(5) If you do not receive a signal the computer will assign you the **accuracy** 50%, as without a signal each outcome is equally likely, 50-50.

Final Cash Payoff. For each participant, three rounds will be chosen at random from the 30 in the experiment: one from rounds 1–10, one from the rounds 11–20, and one from rounds 21–30. For each chosen round you will be entered into a lottery for $7 dollars: your probability of winning that lottery is the number of points you won in that round divided by 250, the total number of points available in a round. For example, suppose that you won 175 points in the randomly determined round, your probability of winning the lottery is $175/250 = 70\%$.

You will each receive a guaranteed show-up fee of $10, so your total earnings can be as high as $31 if you win each of the three lotteries, or as low as $10 if you lose all three.

Practice. When the experiment begins you will be brought to a practice screen where you can experiment with the cutoffs and signals for 5 minutes. You may leave the practice screen at any time by clicking the red **'Leave Practice'** button, but you will not be able to continue until everyone else has also left, or the 5 minutes has run out. No messages will be sent or received by other players in the practice screen, the purpose is to allow each participant to gain a better understanding of the signals and cutoffs before the experiment begins. You may change the cutoff values for sending and receiving messages, and each time you click the **'Try a New Signal'** button the computer will give you a new signal and let you know whether you sent a message or listened to messages at those values of $SEND$ and $LISTEN$.

Good Luck.

Part 2 Instructions

The game will proceed exactly as before except that you will now be given the opportunity to earn an additional payoff. After messages have been sent and received you will be asked to specify the probability with which you think your prediction of the outcome is correct. You must enter a number between 0 and 100 when you choose your prediction of the coin flip, which corresponds to the percentage chance you think the true coin flip was the same as your prediction.

We have devised the payment for this additional task so that if you want to make the most amount of money for this additional question, your best decision would be to enter the true probability you place on your prediction of the coin flip being correct. If you believed that there was an 84% chance that *HEADS* occurred and you are selecting *HEADS* as your prediction, entering 84 is your mathematically optimal response. If you believe there is a 92% chance *TAILS* occurred and you are selecting *HEADS* as your prediction your best response is 8%. Similarly, you should note that the payment from answering this question correctly is small in relation to the possible winnings from the lotteries, the purpose of this question is to gather extra information.

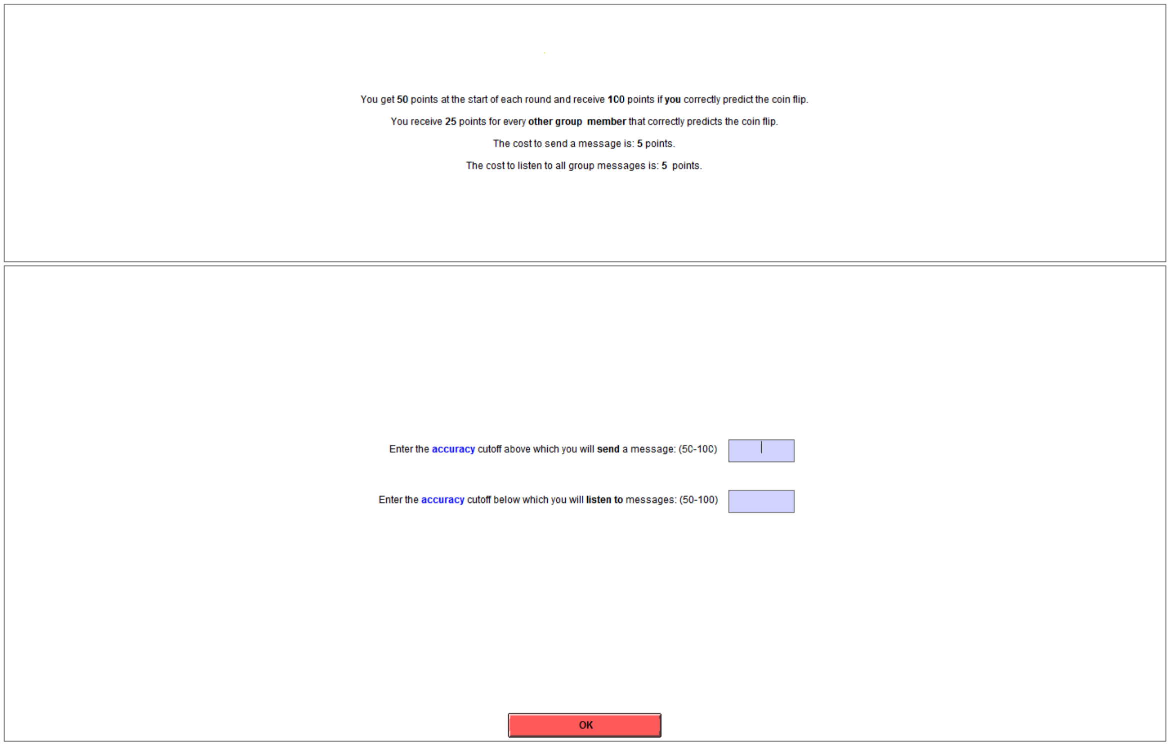
More exactly, if you specify the percentage chance Q you will receive the following payoff:

- If the coin flip is the same as your prediction you will receive $\$1 - (\frac{100\%-Q\%}{100\%})^2$.
- If the coin flip is different from your prediction you will receive $\$1 - (\frac{Q\%}{100\%})^2$.

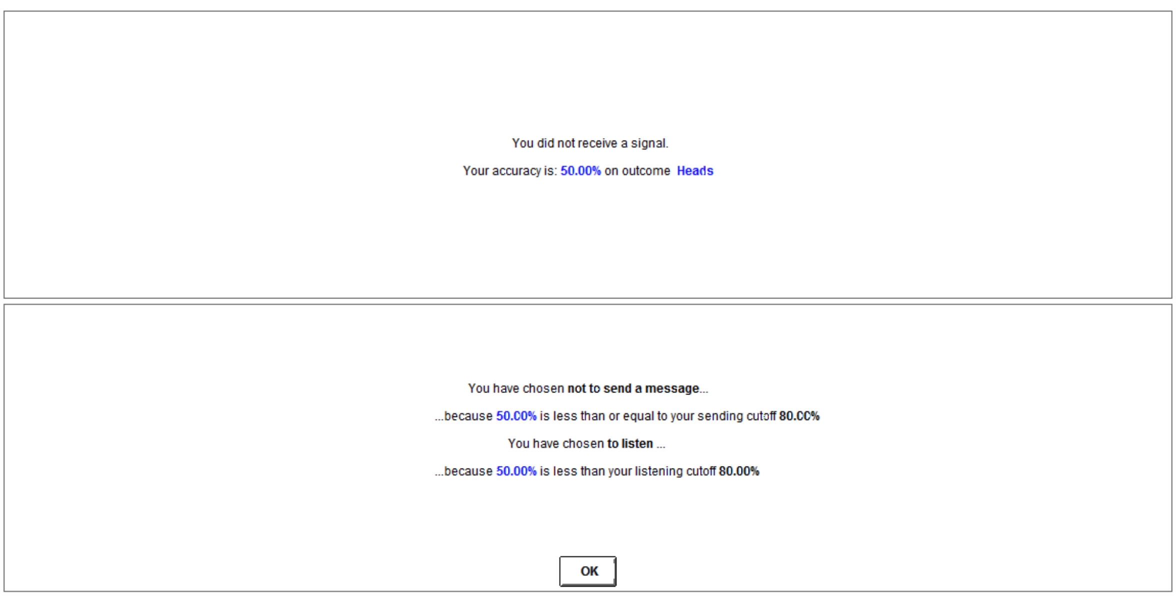
One of the 10 rounds that you play in the second part will be chosen randomly for this additional payment. This payoff is in dollars, not experimental points, and will be added to your total at the end of the experiment alongside any winnings in the final lotteries.

Good Luck.

APPENDIX D. REPRESENTATIVE SCREENSHOTS OF THE INTERFACE

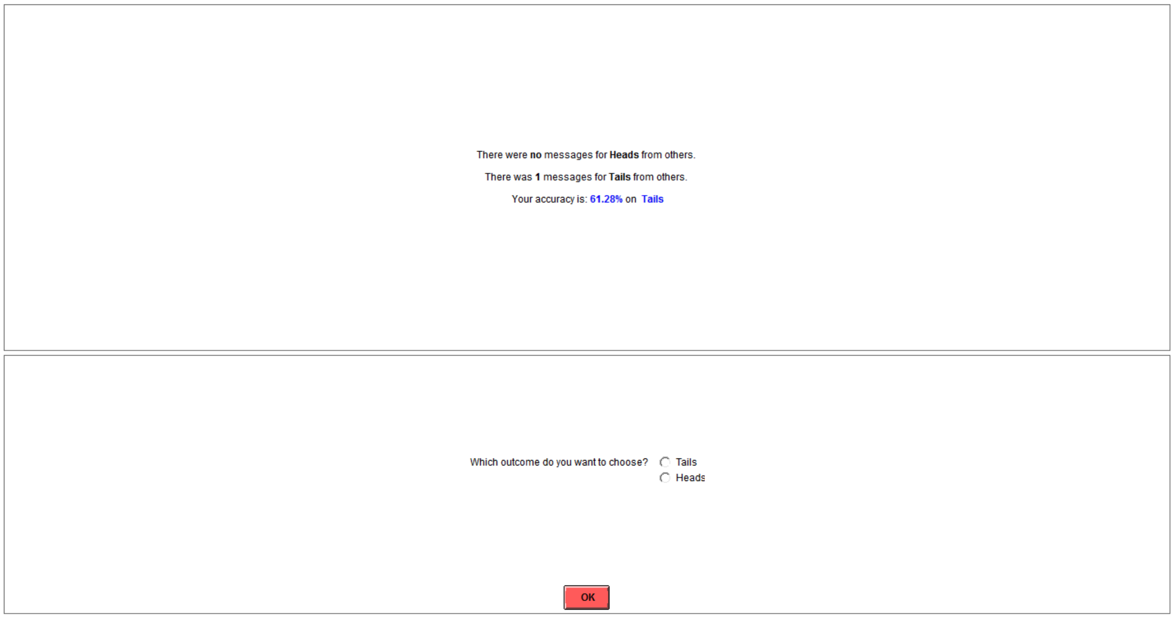


(A) Entering cutoffs



(B) Realization of Information

FIGURE 5. Images of interface I (Not for publication)



(A) Message realization when listening

(B) Round feedback

FIGURE 6. Representative images of interface II (Not for publication)