Essays on the Economics of Communication

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Abstract

Chapter 1 studies the tradeoff of knowledge generation and information flow in organizations, and explains why many modern firms choose to replace corporate meetings with one-on-one communication. In a theoretical model we compare the efficiency of employee communication during a meeting with the efficiency during a pairwise one-on-one communication. The quality of information transmission between agents depends on the accuracy of active communication (talking) and the accuracy of passive communication (listening), which is costly for the agents and is selected prior to communication. In addition, before the communication stage, all agents choose how much to invest in the precision of their private information. We find that meetings make the communication more precise and less costly; however, they have an undesirable effect of reducing incentives for the agents to invest in obtaining their own information. If a firm cannot commit to an optimal communication policy ex-ante, the agents will underinvest in information acquisition and the firm will have to compensate with a larger frequency of meetings. Thus we obtain an inefficiently high equilibrium frequency of meetings due to the lack of commitment by the firms.

Chapter 2 provides an explanation for why many organizations are concerned with "e-mail overload" and implement policies to restrict the use of e-mail in the office. In a theoretical model we formalize the tradeoff between increased productivity from high priority communication and reduced productivity due to distractions caused by low priority e-mails. We consider employees with present-biased preferences as well as time consistent employees. All present-biased employees ex-ante are motivated to read only important e-mail, but in the interim some agents find the temptation to read all e-mail in their inbox too high, and as a result suffer from productivity losses. A unique aspect of this paper is the social nature of procrastination, which is a key to the e-mail overload phenomenon. In considering the firm's policies to reduce the impact of e-mail overload we conclude that a firm is more likely to restrict e-mail in the case of employees with hyperbolic preferences than in the case of time-consistent employees.

Chapter 3 is joint work with Marco Battaglini. We examine strategic information transmission in a controlled laboratory experiment of a cheap talk game with one sender and multiple receivers. We study the change in equilibrium behavior from the addition of another audience as well as from varying the degree of conflict between the sender's and receivers' preferences. We find that, as in cheap talk games with just one receiver, information transmission is higher in games with a separating equilibrium, than in games with only a babbling equilibrium. More interestingly, we find clear evidence that the addition of another audience alters the communication between the sender and the receiver in a way consistent with the theoretical predictions. There is evidence of the presence of agents that are systematically truthful as senders and trusting as receivers. Deviations from the theoretical predictions, however, tend to disappear with experience, and learning is faster precisely in the games where deviations are more pronounced.

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Contents

Chapter 1

Too Many Meetings: Communication in Organizations

1.1 Introduction

Meetings are an important component of the operation of firms, non-profits, government committees and other organizations. According to a Microsoft survey,[1] an average employee spends 5.6 hours a week in meetings. Yet the majority of respondents (69%) consider meetings to be unnecessary and unproductive. The estimates done by Group Vision found that ineffective meetings cost Fortune 500 companies millions of dollars every year. A whole industry of consulting firms[2] appeared to help companies improve their productivity in general and meeting management in particular. Other companies have taken their own initiatives to reduce the number of meetings: Facebook, Inc. officially declared Wednesday to be a "No Meeting Day," and Best Buy along with Gap Outlet, D.C. Office of the Chief Technology Officer, and Office of Personnel Management instituted Results Only Work Environment (ROWE), in which there are no scheduled or required activities at the office.[3]

Given that the organizations themselves choose whether or not to have meetings and how

[1]The Microsoft Office Personal Productivity Challenge (PPC) was conducted in 2005 and collected responses from more than 38,000 people in 200 countries.

[2] Lean Six Sigma, Leadership Coaching, The People-ontheGo, Fusion Factor, Ascend-Works LLC. and many others

[3]A workers output is the only determinant of his or her compensation.

often, the “too many meetings” phenomenon presents somewhat of a puzzle.

In this paper we analyze the two alternative communication structures in the company–one-on-one discussions between employees and team meetings with many employees attending simultaneously. We identify the relative costs and benefits of each, derive the optimal frequency of meetings, and finally provide a possible explanation for the “too many meetings” phenomenon.

We consider a cooperative “team” environment, in which all members of the organization benefit from learning and sharing the same information. Possible examples include a board of directors approving the company budget, a team of software engineers gathering requirements for a project, a group of scientists synthesizing a protein, a hiring committee that is interested in information on the best candidate, a study group of students trying to solve a problem set, etc. Each member of the organization has an opportunity to individually learn about the problem at hand, and then exchange his or her knowledge with other teammates prior to making a final decision. The exchange of knowledge and ideas can happen either during a large organized meeting or through informal one-on-one discussions (small meetings) with coworkers.

Communication is costly and, in the model, is incentivized by the positive spillovers that better decisions by others have on each individual. Each one of a finite number of employees chooses the precision with which to share his or her private information with others (active communication) as well as the precision with which to listen to the reports of others (passive communication). The costs for both active and passive communication are proportional to the precision of communication. Such communication framework with endogenous communication precisions was first developed by Calvó-Armengol et al. (2009). This paper extends their framework to model communication in meetings. Most importantly, it endogenizes the precision of private information that individuals acquire prior to communication.

In particular, agents can pay a cost to invest in getting more precise private information. An agent who incurs a private cost to improve the precision of his or her own signal generates positive spillovers for others, who will learn from him or her through communication.

Because of these externalities, in equilibrium, agents' choices of information acquisition and communication precisions are inefficiently low. Also, relative to the investment in passive communication, agents underinvest in active communication. The organization's communication policy, which is a choice between one-on-one communication and a meeting, aims to minimize these inefficiencies.

We show that communication in meetings has a smaller noise in information transmission than communication in one-on-one setting. This intermediate result arises from the fact that an agent who is speaking in a meeting presents his or her information to many individuals simultaneously and thus has a greater incentive to invest in active communication than when he or she is speaking with just one person in bilateral communication. Furthermore, the complementarity between the equilibrium choice of active and passive communication gives that the equilibrium investment in passive communication is also greater in the case of a meeting than in one-on-one communication.

While meetings facilitate more accurate information transmission, they have costs direct and indirect. Direct costs correspond to the need of coordinating the schedules of all attendees, the resources required to rent a room, a projector and a screen, etc. and are modeled as an exogenous random draw from a pre-determined distribution of costs. The indirect costs are based on an important endogenous drawback of the meetings: when employees anticipate getting precise information at a meeting, they have little incentive to invest personal resources in gathering information prior to the meeting. Therefore, the organization has to weight the benefit of a more efficient exchange of information in meetings with the cost of potentially worse incentives to acquire information due to free-riding by employees.

The organization's preferences for a communication policy thus exhibit a form of time inconsistency. Ex-ante (before agents have an opportunity to invest in their private information), it prefers to announce that only a few meetings will take place to give agents an incentive to "prepare" adequately. On the other hand, ex-post (after investment in information has taken place), it prefers to hold additional meetings, so as to ensure a more efficient exchange of the signals that have been acquired. Two different timelines of events are considered in order to model the firm's lack of commitment. In the first case, the firm credibly commits to a policy before agents make their investments in private information and chooses a smaller probability of meetings to incentivize information generation. In the second case, the firm announces its policy after investment in knowledge generation has taken place, and it chooses a higher probability of a meeting in order to have a more efficient information exchange. If the firm lacks commitment and is not be able to implement its ex-ante optimal policy, it will then suffer from too many unproductive meetings. This is a key result of our paper and the explanation for the "too many meetings" phenomenon.

To the best of our knowledge this paper is the first to show how a form of overcommunication can arise from the lack of commitment by a firm. It is complementary to the findings in Morris and Shin (2002), Morris and Shin (2007), and Chaudhuri et al. (2009), where the focus is on the coordination aspect of public communication. As shown in this literature, an additional benefit of communication during a meeting could be the ease of coordinating actions based on public, rather than private, information. In this paper, we abstract from the direct benefit of action coordination, and instead focus on the tradeoff between more efficient communication in public and better private knowledge with pairwise communication. In addition, we follow Calvó-Armengol et al. (2009) in endogenizing communication precisions and further extend their model to endogenize the precision of private information.

Galeotti and Goyal (2010) use a simple network model to explain why, in social groups, a very small subset of individuals invests in collecting information, while the rest invest in forming connections with these select few. Their approach to studying the tradeoff between information acquisition and dissemination is different, since agents choose to engage in either gathering information or communicating with others. In our model, agents are symmetric and engage in both activities in equilibrium. In addition, the framework in this paper allows for comparisons across communication structures.

This paper also contributes to the literature on communication in organizations by direct comparisons of meetings with one-on-one communication. Crémer et al. (2006) address the benefits and drawbacks of specialized technical language. Weber and Camerer (2003) study the difficulties in communication due to cultural differences, and Weber (2006) describes optimal growth that preserves culture to allow for efficient communication.

The rest of the paper is organized as follows. Section 1.2 formalizes the model. Section 1.3 derives equilibrium of the game with and without commitment. Section 1.4 presents the main result of the paper - comparison of the equilibrium number of meetings with and without commitment, and Section 1.5 concludes. All proofs are gathered in the Appendix.

1.2 The Model

We analyze an organization with n employees, who can talk and learn from each other prior to making a decision about their job assignment. There is a state of the world θ, and that there is no public information about it. Each employee gets a private signal $\theta_i = \theta + \psi_i$, where $\psi_i \sim N(0, \sigma_i^2)$ is a normally distributed noise term, and can engage in costly communication with others in order to exchange private information.

The communication structure in our model is in the spirit of Calvó-Armengol et al. (2009) with individual agents choosing active and passive communication precision prior to information transmission. This is a natural way to model information flow in organizations, so that the quality of the communication channel is determined by both the speaker's effort in transmitting his knowledge and the listener's effort in learning from his or her colleague. We consider two possible settings for the agents to exchange their private information with one another:

- **one-on-one communication** - pairwise communication that occurs between every two players in the company. Prior to the realization of private signals, each player i selects passive(π_{ji}) and active(ρ_{ij}) precisions for communication with player j.

- **Meeting** - company wide meeting, in which *every* employee takes turns addressing everybody else. Prior to the realization of private signals, each player i selects the active(ρ_i) precision for addressing others and the passive(π_{ji}) precision for listening to player j.

The two communication settings modeled in this paper are the two possible extremes of possible sizes of the meeting. Roughly speaking, one can think of *one-on-one communication* corresponding to smaller, spontaneous meetings and *meetings* corresponding to larger, organized affairs in the organization. An interesting extension for future research would allow for size of the meeting to vary, and be determined endogenously in equilibrium by the firm's policy.

In the following two subsections, we formalize the details of the communication environments above and derive the endogenous communication precisions that are chosen by the agents.

1.2.1 One-on-one communication

Information exchange in one-on-one communication occurs for each pair of agents in the organization independently from other pairs, such that the message that player i sends to player j is

$$y_{ij} = \theta_i + \epsilon_{ij} + \delta_{ij},$$

where $\epsilon_{ij} \sim N(0, \rho_{ij}^2)$, and $\delta_{ij} \sim N(0, \pi_{ij}^2)$ are two independent normally distributed noise terms. The ultimate goal of each agent to take an action based on his or her best estimate of the unknown state of the world θ. After the communication stage, player i selects an action such as to minimize the following individual loss function:

$$l_i = (a_i - \theta)^2 - \sum_{j \neq i} d(a_j - \theta)^2 - K_\rho \sum_{j \neq i} \frac{1}{\rho_{ij}^2} - K_\pi \sum_{j \neq i} \frac{1}{\pi_{ji}^2}. \tag{1.1}$$

This quadratic loss function incorporates the agent's own imperfect knowledge of the state ($(a_i - \theta)^2$) as well as a measure of the mistakes made by his or her coworkers ($\sum_{j \neq i} d(a_j - \theta)^2$). Parameter d specifies the strength of team incentives relative to individual incentives. We assume that cooperative environment with $d > 0$. However, we also set $d < 1$, since in most organizations individual incentives are stronger than the team incentives. The final two terms in the loss function in (1.1) are costs of communication. Given the communication intensities, player i selects an optimal action $a_i = \hat{\theta}_i$, where $\hat{\theta}_i$ is the MLE estimator:

$$\hat{\theta}_i = \left(\sum_{j=1}^{n} \frac{y_{ji}}{\sigma_j^2 + \rho_{ji}^2 + \pi_{ji}^2} \right) \Big/ \left(\sum_{j=1}^{n} \frac{1}{\sigma_j^2 + \rho_{ji}^2 + \pi_{ji}^2} \right), \text{ and}$$

$$\hat{\theta}_i \sim N\left(0, \left(\sum_{j=1}^{n} \frac{1}{\sigma_j^2 + \rho_{ji}^2 + \pi_{ji}^2}\right)^{-1}\right).$$

The choice of communication intensities for player i involves maximization of the expected utility. Since $E_i[\theta^2] = Var(\hat{\theta}_i) + (\hat{\theta}_i)^2$, the optimization problem simplifies to:

$$\min_{\{\rho_{ij}^2, \pi_{ji}^2\}_{j \neq i}} Var(\hat{\theta}_i) + \sum_{j \neq i} dVar(\hat{\theta}_j) + K_\rho \sum_{j \neq i} \frac{1}{\rho_{ij}^2} + K_\pi \sum_{j \neq i} \frac{1}{\pi_{ji}^2},$$

which in symmetric equilibrium with $\sigma_i^2 = \sigma^2$ for all i becomes:

$$\min_{\{\rho_i^2, \pi_i^2\}} \underbrace{\frac{1}{\frac{1}{\sigma^2} + \frac{n-1}{\sigma^2 + \rho_*^2 + \pi_i^2}}}_{\text{error from own action}} + \underbrace{\frac{d(n-1)}{\frac{1}{\sigma^2} + \frac{1}{\sigma^2 + \rho_i^2 + \pi_*^2} + \frac{n-2}{\sigma^2 + \rho_*^2 + \pi_*^2}}}_{\text{error from others' actions}} + \underbrace{K_\rho \frac{n-1}{\rho_i^2} + K_\pi \frac{n-1}{\pi_i^2}}_{\text{cost of communication}},$$

where starred values denote the equilibrium choices of other agents. The FOCs with respect to ρ_i^2 and π_i^2 give the following solutions for equilibrium precisions of communication as functions of σ^2:

$$\rho_*^2(\sigma^2) = n\chi(1) \tag{1.2}$$

$$\pi_*^2(\sigma^2) = \sqrt{d\frac{K_\pi}{K_\rho}} n\chi(1), \tag{1.3}$$

where

$$\chi(m) = \frac{K_\rho \sigma^2}{\sqrt{dmK_\rho}\sigma^2 - K_\rho\left(1 + \sqrt{dm\frac{K_\pi}{K_\rho}}\right)}.$$

The equilibrium choice of passive communication is proportional to the precision of active communication. The ratio of the two communication precisions is just the square root of the ratio of the cost of communication multiplied by the teams incentives parameter d. Thus, in a symmetric equilibrium we obtain a complementarity between speaking and listening: agents select higher precision of passive communication in response to a higher precision of active communication and vice versa.

1.2.2 Meeting

In order to streamline (and presumably make more efficient) the communication among employees, a company may choose to hold an organized meeting instead of free-form one-on-one discussions. We assume the simplest possible way to structure a meeting, in which everybody gets a turn to present their information and everybody listens to every speaker. The loss function for an individual who is communicating in a meeting is the following:

$$\tilde{l_i} = (a_i - \theta)^2 + \sum_{j \neq i} d(a_j - \theta)^2 + K_\rho \frac{1}{\tilde{\rho_{ij}}^2} + K_\pi \sum_{j \neq i} \frac{1}{\tilde{\pi_{ji}}^2}, \tag{1.4}$$

where $\tilde{\rho_{ij}}^2$ and $\tilde{\pi_{ji}}^2$ are communication precisions chosen during a meeting. The individual loss function in the case of a meeting is identical to the loss function with pairwise communication, except for the fact that the active cost of communication is just paid once in a meeting instead of $n-1$ times in the case of one-on-one communication. As before, the optimization problem of the expected loss in a symmetric game with precisions of private signal $\sigma_i^2 = \sigma^2$ is:

$$\min_{\{\tilde{\rho}_i^2, \tilde{\pi}_i^2\}} \underbrace{\frac{1}{\frac{1}{\sigma^2} + \frac{n-1}{\sigma^2 + \tilde{\rho_*}^2 + \tilde{\pi_i}^2}}}_{\text{error from own action}} + \underbrace{\frac{d(n-1)}{\frac{1}{\sigma^2} + \frac{1}{\sigma^2 + \tilde{\rho_i}^2 + \tilde{\pi_*}^2} + \frac{n-2}{\sigma^2 + \tilde{\rho_*}^2 + \tilde{\pi_*}^2}}}_{\text{error from others' actions}} + \underbrace{K_\rho \frac{1}{\tilde{\rho_i}^2} + K_\pi \frac{n-1}{\tilde{\pi_i}^2}}_{\text{cost of communication}},$$

where starred values denote the choice of communication precisions by other players. The solution to this maximization problem is

$$\tilde{\rho_*}^2(\sigma^2) = n\chi(n-1) \tag{1.5}$$

$$\tilde{\pi_*}^2(\sigma^2) = \sqrt{d(n-1)\frac{K_\pi}{K_\rho}} n\chi(n-1). \tag{1.6}$$

Just like in the case of one-on-one communication, we note that passive communication is proportional to active communication scaled by a constant term $\sqrt{d(n-1)K_\pi/K_\rho}$. The following proposition summarizes the characterization of a symmetric equilibrium in the communication game for a pairwise setting and for a meeting.

Proposition 1.1 *Given the variance of private signals σ^2 and the communication costs K_ρ and K_π, there exists a unique equilibrium with a positive amount of communication*

1. *in a **pairwise setting** if and only if $d\sigma^4 > K_\rho \left(1 + \sqrt{dK_\pi/K_\rho}\right)^2$ and is characterized by equations (1.2) and (1.3).*

2. *in a **meeting** if and only if $d(n-1)\sigma^4 > K_\rho \left(1 + \sqrt{d(n-1)K_\pi/K_\rho}\right)^2$ and is characterized by equations (1.5) and (1.6).*

Compared to the loss function of an individual in one-on-one communication, the loss function for communication during a meeting exhibits costs savings. Moreover, a message that is spoken during a meeting has a simultaneous effect on $n-1$ individuals compared to just 1 individual in pairwise communication. Since speaking in a meeting has a larger impact, an individual has more incentives to invest in active communication during the meeting than during the one-on-one communication. The cost savings and higher incentives for active communication make information transmission during a meeting more precise, which is the result of the following Proposition.

Proposition 1.2 *In symmetric equilibrium with identical agents, communication during a meeting is more precise than in an one-on-one setting:* $\rho^2 > \tilde{\rho}^2$ *and* $\pi^2 > \tilde{\pi}^2$*, where* $\{\rho^2, \pi^2\}$ *are communication precisions in an one-on-one setting and* $\{\tilde{\rho}^2, \tilde{\pi}^2\}$ *are communication precisions in a meeting.*

Proposition 1.2 demonstrates how and why information transmission is more effective in a meeting. In Section 1.2.4 we will enrich the model by introducing the direct and indirect costs associated with organizing a meeting.

1.2.3 Efficiency of Communication Precisions

Given that communication among agents has positive spillovers on others, we find that individuals do not invest enough in active communication. Agents incorporate their personal benefit from others being better informed, however, they do not take into account the increase in others' utility from better information. Since $0 < d < 1$, the positive externality from active communication is not fully internalized by the speaker, and the precision of active communication is inefficiently low. In addition, we find that relative to the investment in active communication, agents tend to invest too much in passive communication. If $d > 1$, then we obtain opposite results, namely that the active communication precisions are inefficiently high, and that with respect to the active communication the passive communication are inefficiently low.

Proposition 1.3 *Let* $\{\hat{\rho}^2, \hat{\pi}^2\}$ *be the efficient (planner's) equilibrium precisions of active and passive communication, respectively. Then*

- *If $d < 1$,*

$$\frac{\hat{\pi}^2}{\hat{\rho}^2} = \left(\frac{K_\pi}{K_\rho}\right)^{\frac{1}{2}} > \left(d\frac{K_\pi}{K_\rho}\right)^{\frac{1}{2}} = \frac{\pi^2}{\rho^2}$$
$$\hat{\rho}^2 < \rho^2$$

- *If $d > 1$,*

$$\frac{\hat{\pi}^2}{\hat{\rho}^2} = \left(\frac{K_\pi}{K_\rho}\right)^{\frac{1}{2}} < \left(d\frac{K_\pi}{K_\rho}\right)^{\frac{1}{2}} = \frac{\pi^2}{\rho^2}$$
$$\hat{\rho}^2 > \rho^2$$

The proof of Proposition 1.3 follows directly from the FOCs as shown above.

1.2.4 Investment in Information Acquisition

We now abstract from the assumption that agents are endowed with their private information prior to the communication game, and endogenize precisions of the private signals. The costly information acquisition will give agents incentives to free-ride of the information disseminated in meetings, which will result in the indirect cost of organizing a meeting. This idea is the key behind the main result of the paper that there could be too many meetings. We endogenize the precisions of private information by allowing the agents to invest in obtaining better information through their private signal. The cost of obtaining a signal with variance σ^2 is $K\frac{1}{\sigma^2}$, and the final utility in a symmetric equilibrium is:

$$\begin{aligned}
-\,u_i(\sigma_i^2, \rho_i^2, \pi_i^2 | \sigma_*^2, \rho_*^2, \pi_*^2) =& \\
&\frac{1}{\frac{1}{\sigma_i^2} + \frac{n-1}{\sigma_*^2 + \rho_*^2 + \pi_i^2}} + \frac{d(n-1)}{\frac{1}{\sigma_*^2} + \frac{1}{\sigma_i^2 + \rho_i^2 + \pi_*^2} + \frac{n-2}{\sigma_*^2 + \rho_*^2 + \pi_*^2}} \\
&+ K_\rho \frac{n-1}{\rho_i^2} + K_\pi \frac{n-1}{\pi_i^2} + K\frac{1}{\sigma_i^2},
\end{aligned}$$

for one-on-one communication, and

$$\begin{aligned}
-\,\tilde{u}_i(\tilde{\sigma}_i^2, \tilde{\rho}_i^2, \tilde{\pi}_i^2 | \tilde{\sigma}_*^2, \tilde{\rho}_*^2, \tilde{\pi}_*^2) =& \\
&\frac{1}{\frac{1}{\tilde{\sigma}_i{}^2} + \frac{n-1}{\tilde{\sigma}_*^2 + \tilde{\rho}_*{}^2 + \tilde{\pi}_i{}^2}} + \frac{d(n-1)}{\frac{1}{\tilde{\sigma}_*^2} + \frac{1}{\tilde{\sigma}_i{}^2 + \tilde{\rho}_i{}^2 + \tilde{\pi}_*{}^2} + \frac{n-2}{\tilde{\sigma}_*^2 + \tilde{\rho}_*{}^2 + \tilde{\pi}_*{}^2}} \\
&+ K_\rho \frac{1}{\tilde{\rho}_i{}^2} + K_\pi \frac{n-1}{\tilde{\pi}_i{}^2} + K\frac{1}{\tilde{\sigma}_i^2}
\end{aligned}$$

for communication during a meeting, with starred values referring to the equilibrium choices of other players.

The first four out of the five components in $u_i(.)$ and $\tilde{u}_i(.)$ above come from the communication loss functions defined in equations (1.1) and (1.4) and contain the expected loss from own mistake in the action, the expected loss from the mistakes of others (scaled by parameter d) and the costs for active and passive communication. The last term is the additional cost agent i pays to obtain a private signal with variance σ_i^2.

1.2.5 Firm's Policy

In order to abstract from the standard agency problem and focus on issues specific to communication, we model the firm simply as the aggregation of its workers and therefore the utility function (loss function) for the firm is identical to the individual utility function. The firm chooses the communication policy, i.e. whether agents are to attend a meeting or to communicate via pairwise interactions. In order to organize a meeting, a firm must incur a random cost $c \sim F(c)$, for some CDF $F(c)$ with support in $[0, \bar{c}]$. While the CDF $F(c)$ is common knowledge, and the firm knows the actual realization of c prior to selecting its policy, the employees of the company might or might not know the realization of c. The interpretations for the two assumptions are different, but the main results hold for both of them. Thus, the firm's loss function is:

$$L = \begin{cases} -u(\sigma_*^2, \rho_*^2, \pi_*^2), \text{ for pairwise communication} \\ -\tilde{u}(\sigma_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2) + c, \text{ for a meeting,} \end{cases}$$

where $u(\sigma_*^2, \rho_*^2, \pi_*^2) = u_i(\sigma_*^2, \rho_*^2, \pi_*^2 | \sigma_*^2, \rho_*^2, \pi_*^2)$ and $\tilde{u}(\sigma_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2) = \tilde{u}_i(\tilde{\sigma}_*^2, \tilde{\rho}_*^2, \tilde{\pi}_*^2 | \tilde{\sigma}_*^2, \tilde{\rho}_*^2, \tilde{\pi}_*^2)$ for all i in a symmetric equilibrium.

If the firm is able to commit to its optimal policy, it is able to influence agents' investment (and therefore) communication decisions. By announcing that there will be no meeting it is able to give individuals more incentives to invest in getting better private signals. However, ex-post (after individuals' investment in information acquisition) the firm always prefers to hold a meeting, since it would improve the communication precision without the undesirable effect of lowering investment in information gathering. This time-inconsistency in the firm's

Figure 1.1: Timeline of Events with Commitment

preferences will lead to a different equilibrium with lack of commitment for the firm. In the following analysis, we consider both cases.

1.3 Equilibrium Characterization

1.3.1 With Commitment

We begin the analysis of the joint equilibrium with employees and the firm by considering a case with commitment, meaning that the firm is able to commit to its optimal communication policy prior to individual investments in private information. Events take place in the order represented in Figure 1.1:

1. The firm learns the realization of the meeting cost and announces whether or not a meeting will take place

2. Agents invest in gathering information

3. Agents choose active and passive communication precisions

4. Agents choose their actions and obtain payoffs

In the case when the firm is able to commit to a communication policy, it does not matter in equilibrium whether or not agents know the actual realization of the meeting cost. Since agents' decisions depend on the cost only indirectly through the firm's choice of a communication policy, and the firm announces whether or not there will be a meeting *before* agents make their investment decisions, the equilibria with and without common knowledge of the realization of the costs is identical. We proceed to solve (by backward induction) for Perfect Bayseian Equilibrium of the game with commitment. In the last stage, agents select communication precisions by minimizing their loss function in pairwise communication:

$$\frac{du_i(\sigma_i^2, \rho_i^2, \pi_i^2|\sigma_*^2, \rho_*^2, \pi_*^2)}{d\rho_i^2} = 0 \tag{1.7}$$

$$\frac{du_i(\sigma_i^2, \rho_i^2, \pi_i^2|\sigma_*^2, \rho_*^2, \pi_*^2)}{d\pi_i^2} = 0, \tag{1.8}$$

and in a meeting:

$$\frac{d\tilde{u}_i(\tilde{\sigma}_i^2, \tilde{\rho_i}^2, \tilde{\pi_i}^2|\sigma_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2)}{d\tilde{\rho_i}^2} = 0 \tag{1.9}$$

$$\frac{d\tilde{u}_i(\tilde{\sigma}_i^2, \tilde{\rho_i}^2, \tilde{\pi_i}^2|\sigma_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2)}{d\tilde{\pi_i}^2} = 0. \tag{1.10}$$

These FOCs give solutions for symmetric communication intensities: $\rho_*^2(\sigma^2)$, $\pi_*^2(\sigma^2)$, $\tilde{\rho_*}^2(\sigma^2)$, and $\tilde{\pi_*}^2(\sigma^2)$, characterized by equations (1.2), (1.3), (1.5), and (1.6) as functions of σ_*^2.

Next, we solve for the optimal investment in information acquisition. Regardless of whether or not agents know the actual realization of the cost of organizing a meeting, c, they make their investment decisions after the firm has already committed to its communication policy. Therefore, if agents expects to have pairwise communication, each agent selects σ_i^2 to minimize:

$$u_i(\sigma_i^2, \rho_i^2, \pi_i^2|\sigma_*^2, \rho_*^2, \pi_*^2),$$

and if agents expect to have a meeting, each agent selects $\tilde{\sigma_i}^2$ to minimize:

$$\tilde{u}_i(\tilde{\sigma_i}^2, \tilde{\rho_i}^2, \tilde{\pi_i}^2|\sigma_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2).$$

By the Envelope theorem, $\frac{du_i}{d\sigma_i^2} = \frac{\partial u_i}{\partial \sigma_i^2}$ and $\frac{d\tilde{u}_i}{d\tilde{\sigma_i}^2} = \frac{\partial \tilde{u}_i}{\partial \tilde{\sigma_i}^2}$, therefore FOCs that define σ_*^2 and $\tilde{\sigma_*}^2$ simplify to:

$$\frac{\partial u_i(\sigma_i^2, \rho_i^2, \pi_i^2|\sigma_*^2, \rho_*^2, \pi_*^2)}{\partial \sigma_i^2} = 0 \text{ and } \frac{\partial \tilde{u}_i(\tilde{\sigma_i}^2, \tilde{\rho_i}^2, \tilde{\pi_i}^2|\sigma_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2)}{\partial \tilde{\sigma_i}^2} = 0. \tag{1.11}$$

We summarize the results for agents' symmetric equilibrium in the following proposition. Proof of uniqueness as well as the derivation of the closed-form solution can be found in the Appendix.

Proposition 1.4 *Given the firm's choice of communication policy, there is a unique symmetric Perfect Bayesian Equilibrium* $\{\sigma_*^2, \tilde{\sigma}_*^2, \rho_*^2, \pi_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2\}$ *for employee investment in information and communication strategies, which is defined by equations (1.2), (1.3), (1.5), (1.6), and (1.11).*

We have already pointed out in Proposition 1.3 that agents' choice of active communication precisions is too low compared to the efficient (planner's) equilibrium, since employees do not fully internalize the benefit for their co-workers obtaining a more precise signal from them. Similarly, when the number of employees n is large, the choice of investment in information acquisition involves a positive externality on others, which is not fully internalized by individual agents. In Proposition 1.5 we compare the FOCs for individuals and for the planner to show that when n is large enough, the individual choice of σ^2 is higher compared to the socially optimal level $\hat{\sigma^2}$.

Proposition 1.5 *Under either of the communication policies - meetings or pairwise communication - the individual choice of investment in information acquisition is inefficiently low compared to the planner's solution, i.e.* $\sigma_*^2 > \hat{\sigma}_*^2$ *and* $\tilde{\sigma_*}^2 > \hat{\tilde{\sigma}}_*^2$*, for any sufficiently large* n*.*

Meetings allow agents to save on communication costs, since each agent reports just once, instead of $n-1$ times. In addition, a larger audience provides for higher incentives to invest into active communication. Because of this, agents who anticipate attending a meeting expect to receive high quality information at the meeting and thus have a smaller incentive to invest in gathering their own information. We check this intuition in the following proposition. In Section 1.3.2 we extend this result to show that agents' investment decreases in anticipated probability of a meeting in the case when there is no commitment by the firm.

Proposition 1.6 *Under the communication policy that involves a meeting, the equilibrium investment in information acquisition is less than the investment under the policy of pairwise communication* $\tilde{\sigma_*}^2 > \sigma_*^2$*.*

Proposition 1.6 demonstrates that agents view information acquisition and communication as substitutes to improve their knowledge of the state of the world. This substitutability comes from the decreasing returns to information that is specified by agents' loss function. This is also in contrast with the complementarity of active and passive communication precisions demonstrated in Proposition 1.1. In the communication game, information

Figure 1.2: Timeline of Events without Commitment

transmission is determined by the quality of active commutation and by the quality of passive communication. Taking the choice of communication precisions by other players as given, a particular agent is selecting simultaneously how much to invest in speaking with other agents and how much to invest in listening to others. In equilibrium, the ratio of the two communication precisions is equal to the ratio of communication costs scaled by team-incentives parameter d. Thus, in symmetric equilibrium we obtain that more investment in active communication corresponds to more investment in passive communication.

The firm faces a tradeoff between better quality of communication in meetings and more precise private information agents receive if they do not anticipate a meeting. Taking into account the additional cost of organizing a meeting, the firm chooses to commit to having a meeting if and only if:

$$c < u(\sigma_*^2, \rho_*^2, \pi_*^2) - \tilde{u}(\tilde{\sigma_*}^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2),$$

i.e. for $c \in [0, c_c]$, where $c_c = u(\sigma_*^2, \rho_*^2, \pi_*^2) - \tilde{u}(\tilde{\sigma_*}^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2)$. Therefore, the ex-ante (prior to the firm learning the realization of the cost) probability of having a meeting is $F(c_c)$. Next, we characterize the equilibrium for the case when firm is not able to commit to its optimal policy, and agents' choice of investment in information comes before the announcement of the policy.

1.3.2 Without Commitment

In the case when the firm is not able to commit to an optimal communication policy, the timeline of events is different and is depicted in Figure 1.2:

1. Agents invest in gathering information

2. The firm learns the realization of the meeting cost and announces whether or not a

meeting will take place

3. Agents choose active and passive communication precisions

4. Agents choose their actions and obtain payoffs

As before, $\{\rho_*^2, \pi_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2\}$ are defined as functions of σ_*^2 by equations (1.2), (1.3), (1.5), and (1.6). In this case, the Perfect Bayesian Equilibrium value for investment in information acquisition and the firm's choice of policy depends on whether or not agents are aware of the actual realization of the meeting cost, c. First, we consider the case of common knowledge of the meeting cost.

Meeting cost is common knowledge

In the case with no commitment, the firm is choosing its communication policy *after* the agents have made their investment in information decisions. Therefore, the firm compares utilities just from the communication stage, defined by:

$$v(\sigma_*^2) = u(\sigma_*^2, \rho_*^2, \pi_*^2) + \frac{K}{\sigma_*^2}$$
$$\tilde{v}(\tilde{\sigma_*}^2) = \tilde{u}(\tilde{\sigma_*}^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2) + \frac{K}{\tilde{\sigma_*}^2},$$

for utility from pairwise communication and from the meeting, respectively, where ρ_*^2, π_*^2 are evaluated at σ_*^2 and $\tilde{\rho_*}^2, \tilde{\pi_*}^2$ are evaluated at $\tilde{\sigma}_*^2$.

First, consider the case when the realization of the cost c is common knowledge. If agents anticipate no meeting, the firm will in fact not choose a meeting as long as

$$c > v(\sigma_*^2) - \tilde{v}(\sigma_*^2) = c_{nc}^1.$$

On the other hand, if agents anticipate a meeting, the firm will in fact choose a meeting as long as

$$c < v(\tilde{\sigma_*}^2) - \tilde{v}(\tilde{\sigma_*}^2) = c_{nc}^2 > c_{nc}^1,$$

because $v(\sigma^2) - \tilde{v}(\sigma^2)$ is increasing as σ^2 is increasing, which is the result of Lemma 1.1. Intuitively, this difference represents the relative benefit of communication in a meeting compared to communication in pairwise setting. It is increasing because of the convexity of the loss function l_i defined in equation (1.1).

Lemma 1.1 *For any company size, the relative gain from communication during a meeting compared to communication in pairwise setting is increasing as the noise of private information is increasing, i.e.* $v(\sigma^2) - \tilde{v}(\sigma^2)$ *is increasing as* σ^2 *is increasing.*

Thus, there are two possible equilibria, involving strategy cutoffs c^1_{nc} and c^2_{nc} for the firm. Figure 1.3 shows the equilibrium policy of the firm as a function of the realized cost c. When the size of the company is large enough, we obtain that $c^1_{nc} > c_c$ and $c^2_{nc} > c_c$ for all parameter values. The proof for these comparisons follows from Proposition 1.10 and is demonstrated in the Appendix. Intuitively, agents' investment in information acquisition is inefficiently low compared to the planner's solution. This is because agents do not fully internalize the positive externality that their improved private information has on the utility of others. Therefore, loss functions u and $\tilde{u}$ actually decrease when σ^2 decreases, i.e. agents have better private information. These relations therefore allow us to conclude that under either of the two equilibria, the ex-ante probability of meeting is higher than in the case with commitment, since:

$$F(c_c) < F(c^1_{nc}) < F(c^2_{nc}).$$

As we discuss in greater detail later, this result does not hold for small n. When the size of the company is small, the firm's announcement of pairwise communication has a direct effect of reducing the noise in the private information, but also an indirect effect of increasing the noise in communication precisions. For certain combinations of parameters, the second "negative" effect is greater than the benefit from better private information. In such cases, a firm that can commit to its communication policy will find it beneficial to actually announce a meeting more frequently than when it does not have access to commitment.

We summarize the characterization of equilibrium in the case with no commitment and public knowledge of costs in the following proposition.

Proposition 1.7 *In the case when the firm lacks commitment and the cost of the meeting is common knowledge, the equilibrium strategies for the agents* $\{\sigma^2_*, \rho^2_*, \pi^2_*, \tilde{\rho_*}^2, \tilde{\pi_*}^2\}$ *are determined by equations (1.2) - (1.6) and (1.12). The equilibrium communication policy is*

- *"Meeting," if* $c < c^1_{nc}$

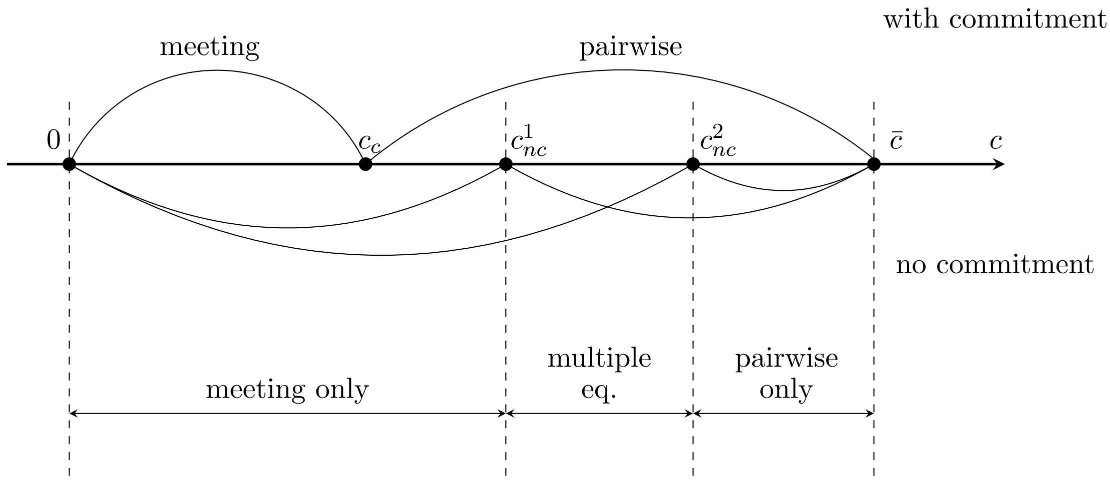

Figure 1.3: Equilibrium communication policy when cost realization is public

- *"Pairwise communication," if* $c > c_{nc}^2$
- *Either "Meeting" or "Pairwise communication" if* $c_{nc}^1 < c < c_{nc}^2$,

In the case without commitment, the firm's choice of policy is affected by employees' investment decisions. It turns out that if agents do not invest a lot in information acquisition, the firm will be forced to hold a meeting with a higher probability. This policy will ensure that agents' communication in a meeting can compensate for the fact that private information is too noisy.

Meeting cost is private knowledge of the firm

Next, consider the case when the realization of the meeting cost is private knowledge of the firm, and the agents have information only about the ex-ante distribution of cost, $F(c)$. If agents anticipate that there is a probability $\hat{\alpha}$ that a meeting will take place, they choose σ_i^2 to minimize the individual loss function:

$$U = (1-\hat{\alpha})u_i(\sigma_i^2, \rho_i^2, \pi_i^2 | \sigma_*^2, \rho_*^2, \pi_*^2) + \hat{\alpha}\tilde{u}_i(\sigma_i^2, \tilde{\rho_i}^2, \tilde{\pi_i}^2 | \sigma_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2) + c\hat{\alpha}.$$

By the Envelope theorem, $\dfrac{dU}{d\sigma_i^2} = \dfrac{\partial U}{\partial \sigma_i^2}$, and therefore the FOC that defines σ_*^2 as a function of $\hat{\alpha}$ simplifies to:

$$(1-\hat{\alpha})\frac{\partial u_i(\sigma_i^2, \rho_i^2, \pi_i^2 | \sigma_*^2, \rho_*^2, \pi_*^2)}{\partial \sigma_i^2} + \hat{\alpha}\frac{\partial \tilde{u}_i(\sigma_i^2, \tilde{\rho_i}^2, \tilde{\pi_i}^2 | \sigma_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2)}{\partial {\sigma_i}^2} = 0. \tag{1.12}$$

In a symmetric equilibrium, $\sigma_i^2 = \sigma_*^2$, and $\rho_i^2 = \rho_*^2$, $\pi_i^2 = \pi_*^2$, $\tilde{\rho_i}^2 = \tilde{\rho_*}^2$, $\tilde{\pi_i}^2 = \tilde{\pi_*}^2$ are all evaluated at σ_*^2. Denote the solution to equation 1.12 by $\sigma_*^2(\hat{\alpha})$. If the agents' anticipated probability of meeting $\hat{\alpha}$ is high, then the agents have little incentive to invest in gathering their own information, and therefore the variance of private information is large. This result is formally proved in the following proposition, which is an extensions of Proposition 1.6.

Proposition 1.8 *Increasing the expected probability of meetings leads to a smaller investment in information acquisition by individual employees:* $\dfrac{d\sigma_*^2(\hat{\alpha})}{d\hat{\alpha}} > 0.$

Given $\sigma_*^2(\hat{\alpha})$, the equilibrium probability of a meeting is determined by the following fixed point equation:

$$\alpha_* = F(v(\sigma_*^2(\alpha_*), \rho_*^2, \pi_*^2) - \tilde{v}(\sigma_*^2(\alpha_*), \tilde{\rho_*}^2, \tilde{\pi_*}^2)). \tag{1.13}$$

In the following proposition, we summarize the characterization of equilibrium in the game with no commitment.

Proposition 1.9 *In the case when the firm lacks commitment and the cost of the meeting is private knowledge of the firm, the equilibrium strategies for the agents* $\{\sigma_*^2, \rho_*^2, \pi_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2\}$ *are determined by equations (1.2) - (1.6) and (1.12) as functions of the expected probability of meeting,* $\hat{\alpha}$. *The firm's choice of communication policy involves a cutoff* c_n*, such that* $\hat{\alpha} = F(c_n)$. *Such equilibrium exists for any distribution of* c*, and depending on the CDF* $F(c)$ *it may or may not be unique.*

Following the intuition for the case when the realization of the cost, c, is public, next we compare the frequency of the meetings with and without commitment for the case of cost being the private knowledge of the firm.

1.4 Number of Meetings

We can now compare the equilibrium policies in cases with and without commitment, and show that when the firm lacks commitment and when the number of employees is large enough, it is more likely in equilibrium to choose a meeting compared to the case without commitment. Since a firm with commitment can always implement the same policy as a firm without commitment and because the firm is a benevolent planner, the equilibrium with commitment corresponds to the first-best allocation. Thus, there will be an inefficiently high frequency of meetings if the firm is large and lacks commitment. Let α_c and α_n be equilibrium probabilities of meeting in the cases with commitment and without commitment, respectively. Then, the following proposition holds.

Proposition 1.10 *Assume that the parameter values are such that there exists communication with positive finite precisions both in a pairwise setting and in a meeting and there is positive finite investment in private information acquisition. Then $\alpha_c < \alpha_n$ for any equilibrium without commitment as long as the number of employees n is sufficiently large.*

The intuition for the case when the realization of the cost of a meeting is common knowledge has been explained above. In the case when the actual cost of the meeting is private knowledge of the firm, we use the fixed point equation (1.13) to show that if n is large enough, then any equilibrium cutoff for the firm without commitment is higher than the equilibrium cutoff for the firm with commitment. The details of the proof can be found in the Appendix.

As we have shown above, compared to the optimal planner's (firm's) solution, agents underinvest in information acquisition and in active communication, because they do not fully internalize the positive externalities that these actions have on their co-workers. Commitment to a communication policy gives the firm a tool to influence the amount of investment in information acquisition. However, influencing the equilibrium σ^2, the firm also indirectly affects communication precisions $\rho^2(\sigma^2)$ and $\pi^2(\sigma^2)$. Since $\rho^2(\sigma^2)$ and $\pi^2(\sigma^2)$ are decreasing functions of σ^2, improvement in information gathering will inevitably lead to a decrease in communication precisions. Thus, in applying its policy via commitment, the firm has to weight these two opposing effects.

It turns out that as n becomes very large, the undesirable effect on communication precisions vanishes, and therefore the firm will choose to announce meeting with a smaller probability in the case with commitment than in the case without commitment. On the other hand, for some parameter values the effect on communication precisions might dominate for small n, and the firm will actually announce a meeting with a larger probability in the case with commitment than in the case without commitment in order to improve precisions in the communication stage.

Intuitively, when n is small, the cost of communication can be relatively small compared to the cost of information acquisition. On the other hand, as the number of people in the firm grows, the total cost of communication increases whereas the cost of information acquisition stays the same. Therefore, with large n, it must be beneficial for the firm to incentivize information acquisition, and it will choose a policy with a smaller number of meetings to do so. Please see the proof of Proposition 1.10 in the Appendix for an example of parameter combination that produces more meetings with commitment. The formal demonstration of the intuition above is also presented in the Appendix.

1.5 Conclusion

This paper develops a setting to study corporate communication. It compares and contrasts communication in meetings vs. one-on-one communication. We show that because of the savings in communication costs and the larger impact of speaking in a meeting, agents transfer information with more precision during a meeting than in one-on-one communication. On the other hand, endogenizing the information acquisition by individual agents shows that precisely the fact that information obtained at a meeting is better, reduces agents' investment in private information, and that the two can be viewed as substitutes. The firm weighs the tradeoff of gains from more efficient information transmission in a meeting with losses from smaller investment in information gathering when agents expect to attend a meeting and selects the optimal communication policy. We show that in the case when a firm lacks commitment, the equilibrium frequency of meetings is higher than the ex-ante policy that the firm would choose with commitment.

The model's policy implications are more pronounced for organizations that put higher weight on information gathering rather than pure coordination of actions among employees. In such companies, it is crucial for the firm to commit to a communication policy to incentivize sufficient information acquisition by its employees. This paper fills the gap in addressing just the information transmission aspect of communication. It can be combined with the previous literature on the coordination aspect of communication to derive more general policy implications.

Among other directions of future research are the endogenizing the size of the meeting and the frequency of meetings as well as allowing the meeting cost function to depend on the number of attendees. This model also provides a tractable set-up for exploring more general communication structures with sequential communication stages and more general organizational structures, such as non-benevolent firms.

Chapter 2

Networking or Not Working: A Model of Social Procrastination from Communication

2.1 Introduction

A goal found among every company's objectives is improving its internal communication and collaboration. The last 40 years of technological progress have allowed organizations to minimize the time and cost of communication, but have at the same time created new challenges. According to the fourth annual Email Addiction Survey, conducted by AOL Mail on June 11-18, 2008, almost half (46%) of 4,000 e-mail users surveyed said that they are "hooked" on e-mail. The knowledge economy research firm Basex estimated that information overload had cost the U.S. economy a minimum of $650 billion in 2007 and $900 billion in 2008. E-mail contributes to this cost through the constant distractions it creates for senders and, especially, recipients, resulting in the loss of time and productivity.

The distracting nature of e-mail communication has proved to be costly in an office environment. Jackson et al. (2003) find that it takes an employee on average 64 seconds to recover from an e-mail interrupt. It would also be wrong to assume that the recipient is able to concentrate on work by ignoring the e-mail, as 70% of e-mails are opened within 6 seconds of arriving and 85% within 2 minutes. In his recent book, Freeman (2009) summarizes many of the negative consequences of e-mail communication and compares it to more traditional modes of communication. Strong terms such as "Death by Email" (used by Jackson) and "Tyranny of the Email" (used by Freeman) suggest that e-mail is a major component of the growing information overload.

The main questions that this paper examines are in what sense there can be "too much e-mail," and what are some of the strategies a company can employ to reduce the overload. Indeed it is somewhat of a puzzle how there can be an e-mail overload when e-mail was adopted as the most efficient means of much-needed communication in companies. Can it ever make sense for a company to restrict e-mail use in the office? What are some other strategies that can be employed in response to the problem? To answer these questions, we develop a model of within firm communication among employees with heterogeneous productivities and degrees of present-bias.

Throughout the paper we will be discussing two types of e-mail communication that are common in any workplace. Before defining them more formally, it is useful to provide two different interpretations that can be used to assess the model empirically. We assume that every worker is occupied by a particular task, e.g. writing a report, solving a problem, doing a computation. If this worker opens his or her mailbox at any time, he or she will most likely find e-mails of two types. In the first interpretation, one type is business-related e-mails, which contain any discussions of reports, problems, or computations relevant for company's production; the other type is e-mails of a social or entertaining nature, such as invitations for dinners, discussions of happy hours, or simply forwards of amusing jokes that do not have direct significance for work. In the second interpretation, all e-mails are work-relevant but have different degrees of urgency. E-mails of the first type are urgent - dealing with them has impact on the task at hand; e-mails of the second type are merely important, but do not have to be written or answered right away.

In either of the two interpretations, we label the first type of e-mail as h-mail (High Priority e-mail), and the second type as l-mail (Low Priority e-mail). More specifically, h-mail includes urgent communication related to a particular task that an agent is occupied with, and boosts his or her productivity on that task. H-mail does not provide the immediate gratification of a completed task; however the prompt attention to it contributes to the worker's long-term productivity payoff. By contrast, l-mail might (in the second interpretation) or might not (in the first interpretation) contain useful communication, but it does not require immediate attention. It does, however, provide an immediate payoff for the agent: in the first interpretation it is the enjoyment from social communication, in the second interpretation it is the satisfaction of completing an easy task (e.g. responding to a memo). This immediate gratification might tempt agents to engage in l-mail instead of doing work.

A defining distinction between h-mail and l-mail is employer's and employee's preferences over them. We consider a model with three periods (0, 1, and 2). While the employer's preferences are always the same, an employee may exhibit present-bias creating a wedge between his or her ex-ante preferences (which are the same as the firm's) and his or her ex-post ones.[4] In our setup every employee has an urgent task to tend to during the day; therefore switching to dealing with fun/non-urgent e-mail during peak productivity time can be viewed as procrastination on the main task. We assume that h-mail and l-mail are such that the firm's preferences as well as employees' ex-ante (period 0) preference rankings over them are as follows:

$$\begin{cases} \text{work} \succeq \text{h-mail} \succeq \text{l-mail}, & \text{for high productivity types} \\ \text{h-mail} \succeq \text{work} \succeq \text{l-mail}, & \text{for low productivity types} \end{cases}$$

In period 1, some employees maintain their preferences, while others switch to the following preferences:

$$\text{h-mail} \succeq \text{l-mail} \succeq \text{work}$$

The model is related to O'Donoghue and Rabin (2002)'s procrastination case with immediate rewards and delayed costs. Like them, we employ a particular form of time-inconsistent preferences ($\beta, \delta-$ preferences)[5] as an explanation for individual procrastination. The key difference, on the other hand, is that we allow for the effect of present-biased preferences

[4] We can thus also think of the firm as a group of productive agents who need to communicate among themselves and will design rules to do so optimally.

[5] Laibson (1997), Loewenstein and Prelec (1992)

of other individuals.[6] This interactive aspect of e-mails is a central part of our mechanism. We will define the degree of present-bias for a population of workers and show that as the population becomes more present-biased, the amount of l-mail increases. Our model thus shows that procrastination can arise from the present-bias of other agents, as a social phenomenon.

The firm's preferences are not going to exhibit present-bias and thus generally the firm will view the equilibrium amount of l-mail as inefficiently high. If a firm is able to observe the distinction between h-mail and l-mail (which is consistent with the first interpretation of h-mail / l-mail being business-related / social), then it can tax low priority communication to achieve efficiency. On the other hand, if the firm is not able to observe (and therefore tax) low priority e-mail directly, it will choose to restrict all e-mail only if the population of workers is sufficiently present-biased.

As in any model with time-inconsistent preferences, it matters whether or not agents anticipate their future actions correctly. Therefore, first we consider the case of naive agents and then compare and contrast it with fully sophisticated agents. For both cases, we derive the comparative statics of the equilibrium amounts of h-mail and l-mail with respect to the present-bias of employee population and compare the effectiveness of the firm's strategies to reduce the e-mail overload. In addition,[7] we present the benchmark case of time consistent employees. We argue that employees' impatience alone is not enough to obtain the results of the paper and present-bias preferences are more appropriate to use in modeling e-mail overload.

Present-biased preferences allow us to model the failure of individual employees to use e-mail optimally. The suboptimal individual choices are exacerbated by the social aspect of e-mail communication. Finally, the firms strategy of regulating e-mail is evaluated in the case of naive, sophisticated and time consistent employees. The paper is organized as follows, Section 2.2 reviews the economics and management literature on information overload. Our

[6]Brocas and Carrillo (2001) also show that the complementarity of actions of several present-biased individuals can exacerbate the tendency to procrastinate and increase the welfare losses. In our model interaction is in the communication activity, which in turn affects payoffs from the production activity.

[7]We thank the anonymous referee for suggesting this discussion.

model is formalized in Section 2.3, and we derive the results for naive agents in Section 2.4. In Section 2.4.1 we characterize the equilibrium amounts of h-mail and l-mail. Section 2.4.2 presents a comparative statics result showing how distribution of present-bias among co-workers may lead to greater procrastination. In Section 2.4.3, we study firm's objectives and different remedies a company can use to address the e-mail overload problem. Section 2.5 studies the case of present-biased workers with fully sophisticated beliefs, and Section 2.6 presents a benchmark case with time consistent employees. Section 2.7 summarizes the discussion and concludes. All proofs are gathered in the appendix.

2.2 Organizational Communication and Information Overload; Review of the Literature

The topic of e-mail and information overload has been previously studied in economics by Van Zandt (2004). In his model of many senders competing for the limited attention of the receivers, too much communication occurs relative to the receivers' bounded ability to process information. In our model, senders of information do not have such an externality on each other, since even if everybody sends e-mails, the distraction cost is assumed to be low enough so that receivers are able to process all messages. Instead, senders all together crowd out time that recipients can devote to work.

Calvó-Armengol et al. (2009) model communication in organizations as a matrix-form game among an arbitrary finite number of players. While their model allows for many types of communication, they focus on positive complementarities from communication and find that communication is inefficiently low compared to the level prescribed by a planner. The inefficiency comes from the fact that a sender of information is motivated to pay the cost of communication only by the hope of coordinating the receiver's action to their own, but he or she does not internalize the positive externality that the receiver gets from the additional information. The flip side of it is that relative to the sender, the receiver is investing too much in the communication, and it is in this very specific sense that this paper obtains inefficiently high communication. In addition, Calvó-Armengol et al. (2009) find that active and passive communication (i.e. investing in, respectively, sending information and receiving information) are strategic complements. In our model the ratio between active and passive communication is not crucial, because all agents who communicate during the day partake in both types of communication in an ex-ante determined proportion.

A separate body of economic literature addresses the problem of multitasking in the principal-agent setting. Holmstrom and Milgrom (1991), Itoh (1992), Itoh (1994), and Hemmer (1995) describe the optimal assignment of tasks under moral hazard and how the best contract is different when the agent faces multiple tasks versus a single task. Mylovanov and Schmitz (2008) extend the literature by simultaneously considering assignment and scheduling of tasks over time. As was described above, our model has a principal-agent flavor only in the interim perspective, since, ex-ante, the company and its workers have the same preferences. Our model also differs from previous work on multi-tasking in that it addresses the inefficiently high amount of multi-tasking overall and the possible causes thereof.

Edmunds and Morris (2000) provide a review of the literature on information overload in the business environment. With respect to e-mail overload, they cite findings based on the analysis of the mailboxes of 20 users along with 34 hours of interviews by Whittaker and Sidner (1997), who find that employees are suffering from the information overload of increasing volume of e-mails they receive. On the other hand, Edmunds and Morris (2000) also reference Kraut and Attewell (1997), whose survey within a multi-national corporation finds that the negative feedback of e-mail is just a perception of being overloaded, whereas the organization in fact benefits from expanded use of e-mail. They argue that the asynchronous nature of e-mail makes it less distracting than other forms of communication, and that transmitted information has a positive effect on firm's output. In their recent paper, Aral et al. (2008) describe a detailed dataset of e-mail messages, accounting data on revenues, employee compensation, and project completion rates at a midsize executive recruiting firm. They measure individual and company output by the number of projects completed and find that it is highly correlated with communication network structure and IT use. Aral et al. (2008) define multitasking as taking on several projects at the same time and show that asynchronous forms of communication and information seeking, such as e-mail and database use increase multitasking, while synchronous forms, such as phone and face to face communication, reduce multitasking. They find that the relationship between multitasking and output is an inverted-U shaped, suggesting that moderate amounts of multitasking increase output, while large amounts reduce efficiency.

Another explanation[8] for "too much e-mail" can be over-optimism: employees may overestimate the probability of receiving an important e-mail and therefore end up constantly checking their inboxes, creating large time-sinks. Indeed, Stafford and Webb (2004) in their book "Mind Hacks," describe the "variable interval reinforcement schedule"[9] mechanism of forming an e-mail checking habit that is very similar to the mechanism that drives gambling addiction. It implies that if rewards (such as receiving information in an e-mail) occur at random times, individuals irrationally overestimate the probability of reward and form a habit of checking "too often". However, e-mail overload arises not just because of too much checking of nonexistent e-mail messages, but also because of too much reading and responding to those that are actually received. In addition, some findings[10] show that deadlines help with procrastination problems,[11] therefore imperfect self-control seems to be a more attractive modeling choice.

Besides enforcing strict deadlines, companies have tried different solutions to alleviate the e-mail overload problem, as summarized below. In our urgent/non-urgent e-mail interpretation, only the agent is able to distinguish between h-type and l-type of e-mail. Consequently, a company can only inform agents of the dangers of distractions, provide a commitment device in terms of enforcing a strict deadline on main work, or limit both types of e-mail communication. In case of work/social e-mail, firms are also able to monitor e-mail traffic and punish individuals who engage in social e-mail too much.

If a company has a technology to monitor its internal e-mail (and many companies in fact already do),[12] it can make checking social e-mail during the day extremely unpleasant

[8]In the spirit of Camerer and Lovallo (1999), Weinstein (1980), and Hoelzl and Rustichini (2005)

[9]See Catania and Reynolds (1968).

[10]Ariely and Wertenbroch (2002), O'Donoghue and Rabin (2008)

[11]And the lack of strict deadlines results in Parkinson (1958)'s law: "Work expands so as to fill the time available for its completion."

[12]Suciu (2009) reports Proofpoint Inc. data security research that shows that companies use employee monitoring for both security and productivity reasons.

for its employees, thus reducing their immediate gratification from it. According to the 2007 Electronic Monitoring & Surveillance Survey from American Management Association (AMA) and The ePolicy Institute, about a quarter of companies have fired employees for e-mail misuse. The companies that find social e-mail to be an offense that justifies firing are still in minority, but in period of layoffs, it can make a difference. Alternatively to a termination, the company's policies might be such that if HR catches an employee doing large amount of social e-mail during the day, his or her reputation and chances for promotion would be hurt.

Instead of monitoring employees, some companies have decided to simply limit the amount of time they are able to spend online. Several companies have been experimenting with e-mail free Fridays and the introduction of regularly scheduled "quiet time" or offline time. Allegedly, the first company to ban e-mail on Fridays was Nestle Rowntree, introducing the rule around 2001.[13] Among the first US companies to introduce such an e-mail policy is Veritas Software; Barnako (2004) reports that an e-mail free Friday policy was introduced at its Silicon Valley offices marketing department in June, 2004. Horng(2007) describes the success of a similar Friday e-mail ban, introduced at Chicago-based U.S. Cellular in August, 2004. He also mentions a similar policy at PBD Worldwide Fulfillment Services. Likewise, as part of their "Next Generation Solutions" to the Information Overload problem, Intel has introduced two pilot programs.[14] In the first one, 300 engineers and managers in two different US locations agreed to observe "quiet time" every Tuesday morning by turning off their email and IM clients and putting a "Do not disturb" sign on their door. After encouraging responses from the first pilot at Intel, the second one was launched a month later and introduced the "Zero Email Friday" to 150 engineers. Both solutions are not mandatory, but rather an encouragement for employees to change their email habits. The fact that many employees do in fact abide by the new rules suggest that workers themselves prefer commitments against future temptation to procrastinate.

Perlow (1999) studied the time use of 17 software engineers who are part of the same team in an anonymous Fortune 500 corporation. After Perlow had observed many distrac-

[13]Chamberlain (2007)
[14]Zeldes (2007a) and Zeldes (2007b)

tions at work, and engineers self-reported resulting loss of productivity, they cooperated in an experiment to implement the division between "quiet time" and "interaction time". The experiment consisted of three phases. In the first phase, 3 mornings a week were allocated as the "quiet time". The second phase was focused on "interaction time" instead, and five days a week 11 A.M till 3 P.M. were declared as such. Engineers inferred that morning until 11 A.M. and afternoons after 3 P.M. were supposed to be "quiet time", however this set up was received less enthusiastically than the first phase. Therefore, in the third phase, the set up from the first phase was repeated to see whether the framing of "interaction time" is less effective than "quiet time" or whether the excitement of the first phase had simply worn off. Improvements in productivity in all phases were reported by the engineers themselves and therefore are subject to confounds; nevertheless this study is among the first to bring attention to the problem of e-mail overload and to illustrate potential solutions.

The third solution for the company is to continue increasing the effectiveness of the e-mail. If somehow the time cost associated with e-mail distraction could be decreased (either on the sending or on the receiving side), then the overall productivity would increase. Mayfield (2008) summarizes some of the most popular behavioral changes that can improve e-mail efficiency: "establishing agreements on the formality, tone, brevity, distribution, responsiveness and timing." Including descriptive subject lines, shorter and to the point e-mails is the etiquette designed to save time for senders and recipients. Burgess et al. (2005) used training sessions and a questionnaire to find that e-mail training can significantly improve the efficiency of e-mail at the workplace.

The fourth (and the most recent) gradual solution for the companies came from the realization that email is not designed for everything. For example, coordinating meetings is more conveniently done through a common online calendar. Similarly, document collaboration is also easier with a common online repository, etc. There are several sets of software packages[15] that allow companies to minimize their dependency on e-mail. A Wall Street Journal article by Vascellaro (2009) has proposed that this is "the End of the Email." If technology and e-mail use move in this direction, we will soon find that h-mail and l-mail

[15]Microsoft's Sharepoint, HyperOffice Collaboration Suite by Hyperoffice, Google Calendar, Google Documents, and others.

communication can be done through different types of media. In this case restricting just the l-mail media at work would be a viable and an effective way to reduce distractions.

Finally, a company that is unable to push any of these gradual changes can resort to the extreme measure of forbidding e-mail altogether. This solution would take away all gains from communication, but at the same time enforce no e-mail distractions at the company. Again, in the extreme case when e-mail distraction can lead to fatalities, some measures have been imposed - many companies have thus been motivated to limit their liability and forbid corporate e-mail while driving.[16] There are also companies that get rid of corporate e-mail altogether. According to a CNN news article on September 19, 2003, high street retailer Phones 4u baned company e-mail for 2500 employees. John Caudwell, the owner of Phones 4U believes that the ban is saving staff three hours a day and his company over 1 million pounds a month. The effectiveness of these solutions for the companies will be analyzed using the theoretical model described in the following section.

2.3 The Model

Consider a continuous measure of workers, working for the same company. Each worker is characterized by a productivity per unit of time type $t \in [0, 1]$ and a present-bias preference parameter $\beta \in [0, 1]$.[17] Employees potentially might have different values of t and β, but the joint cumulative distribution of types $H(\beta, t)$ is common knowledge for all players. Each agent is endowed with 1 unit of time, which he or she can either use completely for work or split between work and communication.

The game consists of three periods - period 0, 1, and 2. At the beginning of the day (period 0), agents arrive at work and are faced with a decision to either work on their main task without distractions or combine it with checking e-mail. Working without distractions allows agents to maximize their productive time. On the other hand, communication boosts workers' productivity while leaving less time to utilize the increased productivity. We

[16]See Potash case described in Richtel (2009).

[17]To separate and contrast the effects of regular discounting and hyperbolic preferences, we first consider present-biased agents with $\delta = 1$. We derive the results for time consistent agents with $\beta = 1$ and $\delta \neq 1$ in Section 2.6.

consider two types - h-mail and l-mail - of communication. Workers are able to either defer l-mail or both types of e-mail until after completing their main task.[18] Thus, in period 0 agents have a choice of deferring all e-mail until after work (strategy ND - No Distractions) or checking e-mail. If an agent is checking e-mail in period 1 he or she has a choice to either engage in h-mail only (strategy H) or in both types (strategy HL) of e-mail. Final productivity payoffs are realized in period 2.

When we say that an agent is checking e-mail during the day, we mean that he or she opens an e-mail program, and skims through the messages. While agents may be able to instantaneously determine whether an e-mail in their inbox is h-mail or l-mail, in order to receive the payoff from reading it, they must pay the distraction cost d in terms of time per e-mail read. In order to simplify the e-mail generating structure, we assume that each agent who reads h-mail during the day also sends 1 h-mail to everybody and spends c units of time writing it. If, in addition, an agent chooses to read l-mail during the day, he or she will similarly contribute 1 e-mail to the volume of l-mail that everybody reads, and pay additional time cost c to write it. Let h, s.t. $0 \leq h \leq 1$ be the measure of workers who choose in period 0 to allow some distractions during the day, and l, s.t. $0 \leq l \leq h$ be the measure of those who choose in period 1 to engage in l-mail during the day. Thus, h also represents the total volume of h-mail, and l represents the total volume of l-mail.

It is important to emphasize the precise definition of time-costs in our model. We assume that, by the end of the day, all agents will have read all of their e-mails. However, only agents who are reading them during the day generate more e-mail. This mechanism is a parsimonious representation of the active vs. passive approach to e-mail communication and corresponds to agents' priorities over work and e-mail. Thus, only workers with an active approach to e-mail will send e-mails and pay the time-cost of writing them. On the other hand, everybody reads e-mail, and therefore the cost of reading e-mail will not be a decisive factor for the workers when choosing strategies. However, if a worker chooses to check e-mail during the day, he or she will have to spend an additional "switching" time of getting their focus back on work. The resulting interpretation of the costs is not the

[18]Workers' productivity during the day is improved by h-mail, therefore deferring h-mail alone is never optimal for the workers.

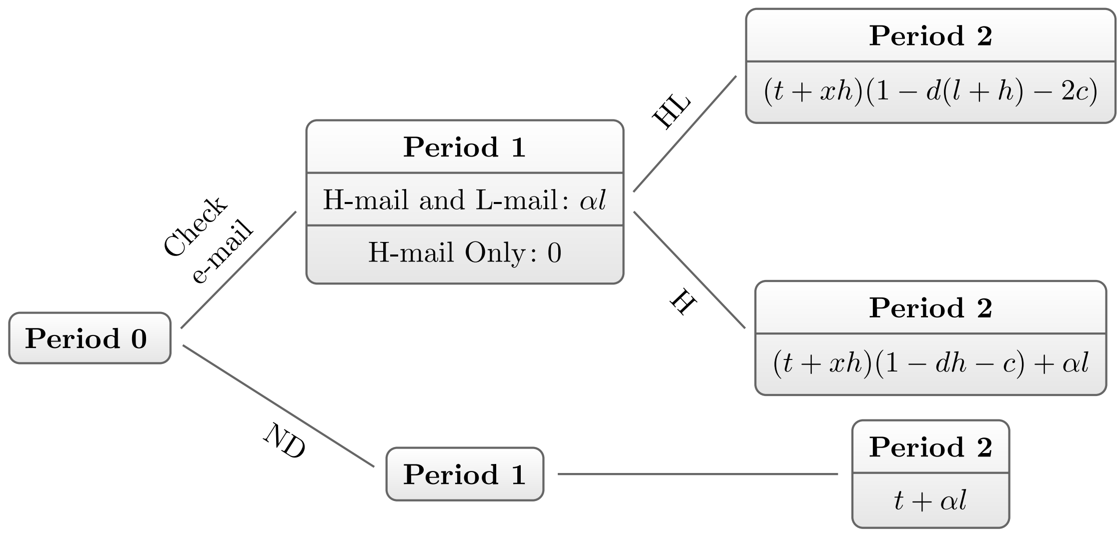

Figure 2.1: E-mail game

time it takes to read the e-mail, since all workers pay this cost whenever they get to e-mail: either during the day or at the end of the day, but rather the additional time-cost of mental distraction created by reading e-mail during the day.

The main benefit of participating in h-mail during the day is the increased productivity per unit of time, which, even if combined with the smaller time left for work, might improve final productivity payoff in period 2 for some workers. We denote by x the size of the productivity boost per h-mail that an agent receives. Therefore if h agents are participating in h-mail, then the effective productivity of a worker of type t who joins in is $t + xh$.

On the other hand, incentives to check l-mail during the day arise only because of its immediate gratification. The payoff is the same regardless of whether an employee reads it during or after work - in both cases it is proportional to l - but from the period 1 perspective, it is either immediate or discounted by $\beta < 1$. We consider the simplest case of the l-mail payoff being equal to αl, where α is a scaling constant, which represents the degree of importance of l-mail relative to a worker's productive payoff in period 2. The three-stage game described above is summarized in game-tree form in Figure 2.1. Individuals have quasi-hyperbolic preferences with regular discount factor $\delta = 1$ and present-bias parameter $\beta \in (0, 1]$. Agent's preferences from the period t perspective (for $t = 0, 1$) take the following form:

$$U^t(u_t, u_{t+1}, ..., u_T) = u_t + \beta \sum_{\tau=t+1}^{T} u_\tau,$$

where $u_0 = 0$, $u_1 = \alpha l$ if the agent chooses to engage in l-mail during the day, and $u_1 = 0$ otherwise; u_2 is $t + \alpha l$, $(t + xh)(1 - dh - c) + \alpha l$, or $(t + xh)(1 - d(h + l) - 2c)$ depending on whether the agent is choosing to work without distractions (ND strategy), check h-mail only (H strategy), or both types of e-mail (HL strategy) respectively.

Present-biased agents ($\beta < 1$) may have correct (sophisticated) or incorrect (naive) beliefs about their future actions as well as the future actions of others and this will matter for the determination of their optimal strategy. Therefore there are four possible assumptions that could be made in modeling agents' beliefs in this game. We shall call beliefs sophisticated if and only if agents are correct about their own future actions and others' future actions. If agents have incorrect beliefs either about their future actions or others' future actions or both, then we call their beliefs naive. In our model, strategy H looks more desirable than HL for any type from the period 0 perspective, therefore the types that possess incorrect beliefs about their own actions are those that expect to choose the H strategy in period 1, but are in fact choosing HL when they are in period 1. Alternatively, incorrect beliefs about others is failing to anticipate that some people will end up choosing the HL strategy in the future. Experiments have shown that at least some fraction of hyperbolic agents have naive beliefs and we begin by considering agents who are naive either about their own future actions, others' actions or both. We leave the discussion of sophisticated beliefs until Section 2.5.

2.4 Naive Agents

It does not in fact matter whether the agent has naive beliefs about his or her own future actions or others' future actions, since in both cases he or she will be expecting to choose the H strategy in period 1 and therefore will be comparing terminal payoffs from H and ND strategies in period 0. This is obviously true if the agent is naive about his or her own future actions. Naivete about others' future actions is the expectation that $l^* = 0$, and this makes H the expected strategy even for a type with correct beliefs about own future

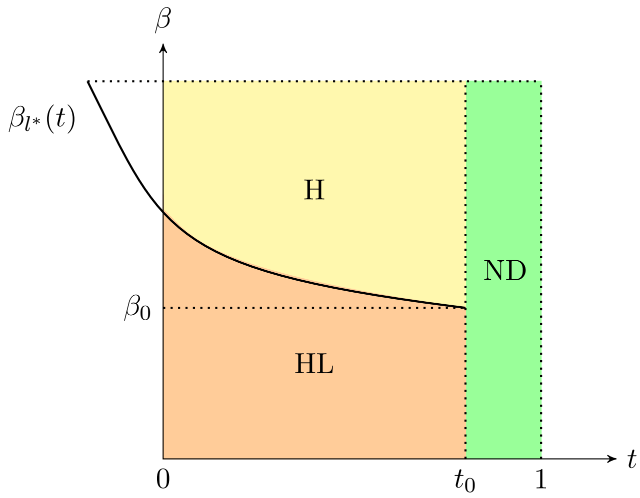

Figure 2.2: Regions of Best Response strategies

actions. Therefore, in period 0 the agent prefers the ND strategy if and only if:

$$\beta[t+\alpha l^*] \geq \beta[(t+xh^*)(1-dh^*-c)+\alpha l^*] \Leftrightarrow$$
$$t \geq \frac{xh^*(1-dh^*-c)}{dh^*+c} \stackrel{\text{def}}{=} t_0.$$

Note that first period decision to check any type of e-mail during the day does not depend on the degree of the individual's present bias. However, we will see that the present bias leads to a time-inconsistency in the period 1 decision of which types of e-mail to engage in. All agents prefer strategy H from the period 0 perspective, but in period 1 some agents prefer strategy HL, namely all types such that:

$$\beta[(t+xh^*)(1-d(l^*+h^*)-2c)]+\alpha l^* \geq \beta[(t+xh^*)(1-dh^*-c)+\alpha l^*] \Leftrightarrow$$
$$t \leq \frac{1-\beta}{\beta}\frac{\alpha l^*}{dl^*+c} - xh^* \stackrel{\text{def}}{=} t_1(\beta).$$

For a fixed h^*, define the boundary β under which agents prefer HL strategy as a function of t and l^*:

$$\beta_{l^*}(t) \stackrel{\text{def}}{=} \frac{\alpha l^*}{\alpha l^* + (t+xh^*)(dl^*+c)}.$$

The regions of individual best response strategies are represented in Figure 2.2 as functions of individual type (t, β). We proceed with characterizing the equilibria of this game.

2.4.1 Equilibrium Characterization

Suppose that the distribution of productivity type t is uniform on $[0,1]$, and the distribution of β is $f(\beta)$ for some continuous density function f with support inside $[0,1]$. If the parameters are such that for the equilibrium values of l^* and h^*, $0 < t_0 < 1$, i.e. the equilibrium is interior, then l and h are determined from the following fixed-point equations:

$$h^* = \int_0^{t_0(h^*)} \int_0^1 f(\beta)\, d\beta\, dt = t_0(h^*) \stackrel{\text{def}}{=} \Psi(h^*) \tag{2.1}$$

$$l^* = \int_0^{t_0(h^*)} \int_0^{\beta_{l^*}(t)} f(\beta)\, d\beta\, dt = \int_0^{t_0(h^*)} F(\beta_{l^*}(t))\, dt \stackrel{\text{def}}{=} \Phi(l^*). \tag{2.2}$$

Equation (2.1) does not depend on l^*, thus we will be able to first characterize equilibrium values for h and then substitute them in equation (2.2) to find the equilibrium values for l. The technical analysis of the cases with single and multiple equilibria as well as the analysis of equilibrium stability are in the appendix. In Theorem 2.1 we present the summary of the characterization of optimal (from firm's point of view) stable equilibrium.

Theorem 2.1 *(Optimal Stable Equilibrium Characterization) Suppose t and β are independent with CDFs $G(t)$ and $F(\beta)$ respectively, and distribution density functions $g(t)$ and $f(\beta)$ with support in $[0,1]$. Then, the optimal stable equilibrium values for h and l are given by:*

(a) $h^* = 0$, $l^* = 0$ *if* $x - xc - c \leq 0$.

(b) $h^* = 1$, $l^* = 0$ *if* $x - x(c+d) - (c+d) \geq 0$, *and* $\frac{\alpha}{c} f(0) \ln\left(\frac{x+1}{x}\right) \leq 1$.

(c) $h^* = 1$, $l^* = \Phi(l^*) < 1$ *is the lowest positive interior solution if* $x - x(c+d) - (c+d) \geq 0$ *and* $\frac{\alpha}{c} f(0) \ln\left(\frac{x+1}{x}\right) > 1$.

(d) $h^* = \frac{x - xc - c}{d(1+x)} < 1$, $l^* = 0$ *if* $x - xc - c > 0$, $x - x(c+d) - (c+d) < 0$, *and* $\frac{\alpha}{c} f(0) \ln\left(\frac{x+1}{x}\right) \leq 1$.

(e) $h^* = \frac{x - xc - c}{d(1+x)} < 1$, $l^* = \Phi(l^*) < h^*$ *is the lowest positive interior solution if* $x - xc - c > 0$, $x - x(c+d) - (c+d) < 0$, *and* $\frac{\alpha}{c} f(0) \ln\left(\frac{x+1}{x}\right) > 1$.

In our analysis we focus only on stable equilibria. In cases when there are multiple stable equilibria, the equilibrium with the lowest amount of l-mail is selected. We assume that the firm is able to influence the selection of a stable equilibrium, and since it prefers the smallest amount of l-mail as possible, this equilibirum will be the most relevant. Characterizing the optimal stable equilibrium gives us an opportunity to study how group present-bias affects the equilibrium number of people checking h-mail and l-mail throughout the day. We will find that some agents allow themselves to be distracted by l-mail only as a result of other people's present-bias.

2.4.2 Social Effect of Present-Bias

Given the heterogeneity of the present-bias parameter β across individuals, we define the notion of one group of employees being more present-biased than another in the sense of a first-order stochastic dominance.

Definition 2.1 *If $F(\beta)$ and $H(\beta)$ are two cumulative distributions for β, then F distribution is less present-biased than H if H First Order Stochastically Dominates F, i.e. $F(\beta) \leq H(\beta)$ for all β.*

If an employee i faces a relatively high CDF of βs for his or her co-workers, he or she knows that a large fraction of them will end up checking both h-mail and l-mail throughout the work day. Since i's own utility of checking l-mail increases as more people connect to the l-mail, as long as he or she is not time consistent ($\beta_i < 1$), employee i will also be more prone to the temptation to play the HL strategy. The spillover effect allows other agents' present-bias to influence the choice of strategy for an agent. In our model, the temptation makes a difference in an employee's choice not only because of their own present-bias (note that β_i can be arbitrary close to 1), but because others are more present-biased.

Theorem 2.2 *Consider two cumulative distributions $F(\beta)$ and $H(\beta)$, s.t. H is more present-biased than F. If l^*_H and l^*_F are two optimal stable equilibria corresponding to the distributions H and F, then $l^*_H > l^*_F$.*

A microblogging site Twitter provides an example of how large the amplifying social effect in Theorem 2.2 can be. Twitter was first launched in 2006, became a separate company in 2007, it is now one of the 50 most popular websites[19] and had a number of unique visitors to grow 1,382%[20] from February 2008 to February 2009. Pear Analytics, a market research firm, analyzed 2,000 tweets[21] to conclude that the larger category (40.55%) of tweeter messages are “pointless babble,” so that in our model it would have been l-mails. It is hard to explain the remarkable popularity of Twitter without the amplifying social effect of procrastinating behavior. If technology continues to move in the direction of becoming even more addictive and distracting then firms will have to take actions to regulate it in the work environment in order to preserve productivity. We will consider some possibilities in the next section.

2.4.3 The firm

Recall that we assumed that the company does not suffer from the standard agency problem and is able to directly incentivize employees for productive tasks. Nevertheless, the preferences for the company that we are about to consider differ from agents’ preferences in two important ways. The first one is the lack of present-bias for the firm, which is a standard assumption. The second one is more subtle and is that l-mail does not directly enter firm’s utility, i.e. $\alpha = 0$ for the firm.

To motivate the $\alpha = 0$ assumption for the firm, recall the two different interpretations for h-mail and l-mail that we had introduced earlier. In the first interpretation, h-mail was business-related e-mail and l-mail was fun/social e-mail, and it is natural to assume that amount of l-mail does not enter firm’s utility function directly, since it does not consider l-mail to be productive. In the second interpretation (urgent/non-urgent e-mail), the firm gains utility from l-mail, since it is merely not urgent, but still business-related e-mail. However, since it is not immediately critical, by definition the firm does not care whether it is completed during the day or at the end of the day. In our model, the agents do not decide whether to read l-mail or not, they only choose whether to do it right away or put off till after the work, therefore the firm does get an additional benefit if its employees

[19] Alexa (2009)
[20] McGiboney (2009)
[21] Kelly (2009)

read l-mail earlier rather than later[22] . The only potential issue with this approach might be the fact that in our simple e-mail generating structure only workers who check e-mail during the day write e-mail, so if the firm prefers nobody to check l-mail during the day, it is not clear who it would expect to write the l-mail. Nevertheless, in urgent/non-urgent interpretation, when the firm cares about l-mail it will treat writing l-mail as a productive task, and therefore it can assign writing low priority mail to some employee as their main job.

We proceed by considering the payoff to the firm as described above and strategies that it might employ to alleviate the e-mail overload problem. If $l^* = 0$, then the firm is already at its optimal equilibrium, which cannot be improved further. In case that optimal stable equilibrium has strictly positive l^*, the output for the firm is given by:

$$\begin{aligned} Y &= \int_0^{h^*}\int_0^{\beta_{l^*}(t)} f(\beta)[(t+xh^*)(1-d(h^*+l^*)-2c)]\,d\beta\,dt \\ &+ \int_0^{h^*}\int_{\beta_{l^*}(t)}^{1} f(\beta)[(t+xh^*)(1-dh^*-c)]\,d\beta\,dt + \int_{h^*}^{1}\int_0^{1} f(\beta)t\,d\beta\,dt. \end{aligned}$$

Simplifying and substituting $h^* = \dfrac{x-xc-c}{d(1+x)}$ gives:

$$Y = \frac{d^2(1+x)^3 + x(c-x+cx)^2}{2d^2(1+x)^3} - \int_0^{h^*} F(\beta_{l^*}(t))(t+xh^*)(dl^*+c)\,dt. \tag{2.3}$$

We discussed earlier a number of strategies that companies use to increase their output. A company can monitor its employees, restrict the amount of time its workers are able to check e-mail, reduce the cost of sending and receiving e-mail, and move away from

[22]Moreover, it might be problematic to include l-mail directly in the firm's utility function in a manner similar to the worker's utility. If we do it, so that the utility function becomes:

$$\begin{aligned} Y &= \alpha' l + \int_0^{h^*}\int_0^{\beta_{l^*}(t)} f(\beta)[(t+xh^*)(1-d(h^*+l^*)-2c)]\,d\beta\,dt \\ &+ \int_0^{h^*}\int_{\beta_{l^*}(t)}^{1} f(\beta)[(t+xh^*)(1-dh^*-c)]\,d\beta\,dt + \int_{h^*}^{1}\int_0^{1} f(\beta)t\,d\beta\,dt \end{aligned}$$

where $\alpha' \in [0, \alpha]$, then an unintended consequence would be that firm cares about the positive externality that agents impose on one another through l-mail. Since individual agents are not internalizing the externality, the firm will actually find present bias to be beneficial, as it would increase the otherwise inefficiently low amount of l-mail. While the firm potentially cares about l-mail, it does not favor it over h-mail or work, and therefore the firm should not be in favor of this positive externality. We find that normalizing firm's utility such that $\alpha' = 0$ will allow to abstract from this externality and focus on the problem of excessive distractions.

depending on e-mail technology for communication. Our model assumes that workers will eventually check all e-mail, and the issue is just whether they check it during the day (and therefore pay additional distraction costs), or after work (without the additional cost). Therefore the strategy of reducing the technological cost of e-mail would correspond to an increase in available time (to some value > 1), and not to the decrease in c or d, which are individual costs. Clearly, this will increase firm's output as agents will have more time to work and to communicate. The strategy of moving away from e-mail technology is not represented in our model directly, and thus will not be considered in detail. We reconsider the rest of the strategies in our theoretical framework and derive conditions under which a company would benefit from each of the strategies relative to the no-action status quo, represented by equation (2.3). Since the two strategies are independent and can be implemented concurrently, we consider the benefits of each separately.

Recall that the first strategy applies only to the work/social e-mail interpretation of our model, but in this case it seems to be among the most prevalent in the companies. This strategy involves investing in an internal surveillance system that monitors all e-mail traffic inside the company. Security concerns are the main reason for such systems, but as was mentioned in the introduction, the Human Resources of the company also utilize the system to enforce the work-related nature of the e-mails. Workers can suffer punishments such as poor reputation, lower bonuses, and even termination as a result of engaging in social e-mail at work. In our model, we represent this as a decrease in α, which creates incentives for workers to quit social e-mail. This strategy does not affect workers' incentives to check work-related e-mail, therefore we should expect an increase in company's output, which is the result of the following theorem.

Theorem 2.3 *Consider an equilibrium with $l^* > 0$, then $\dfrac{dl^*}{d\alpha} > 0$ and $\dfrac{dY}{d\alpha} < 0$.*

The proof is relatively straightforward and can be found in the Appendix.

In European companies, an employer's ability to decrease α is limited by privacy laws. In the US and in Europe, harsh punishment may prompt workers to leave for other employers. In addition, in the context of the second urgent/non-urgent interpretation of our model, the company is simply not able to distinguish h-mail from l-mail. The bounds on the effectiveness of surveillance strategies push companies to try alternative methods, such as limiting the amount of time employees are able to check the e-mail. It is interesting to note that European firms (UK to be precise) were among the first to experiment with no-email Fridays. In our model, this will be represented by $\tau < 1$ units of time available for agents to allocate towards work, work-related e-mail, or social e-mail, and for $1 - \tau$ units of time agents will be required to work. Thus, under such policy, the payoffs of the agents become the weighted average of the payoff they used to have (weight τ) and payoff from work t (weight $1 - \tau$). In contrast to the first strategy, it is not always beneficial for the firms to restrict e-mail time. While it indeed limits the volume of social e-mail, it may also reduce the work-related communication, which can lead to output losses for the company. The following theorem derives conditions under which small restrictions of communication time lead to an output increase.

Theorem 2.4 *Let the firm be in equilibrium with $l^* > 0$ and introduce an e-mail policy such that $\tau \in (0, 1)$ is the time available to employees for communication. This policy reduces the equilibrium amounts of h-mail and l-mail and is beneficial to the firm, i.e. $\left.\frac{dY}{d\tau}\right|_{\tau=1} < 0$, if the population of workers is sufficiently present-biased.*

The proof in the Appendix includes the description of worker's strategies and equilibrium output in this modified game, which is followed by the derivation of the condition on $F(\beta)$ that guarantees that $\tau < 1$ restriction leads to a higher output.

Therefore, the first strategy - monitoring and punishing employees for excessive use of social e-mail is always an effective way to increase productivity, while the second one - restriction of all e-mail is only effective for a sufficiently present-biased pool of individuals. Given that many companies have already invested in monitoring capital for security reasons, the marginal costs of using it for enforcing productive communication are low, and we indeed find many companies doing it. The parameter conditions that guarantee the effectiveness of e-mail restrictions imply that not all companies have incentives to pursue such strategies, and in fact we do not find it to be as common as e-mail monitoring.

2.5 Sophisticated Agents

Up until now we have assumed that agents hold naive expectations either about both others' and their own actions or about just others' actions. In this section we consider the case of fully sophisticated agents with correct beliefs about all future actions. We will highlight the differences in strategies that arise as a result of sophisticated beliefs, prove a comparative statics result that parallels Theorem 2.2, and once again review the firm's strategies.

2.5.1 Equilibrium Characterization

In equilibrium with h, l amounts of high-priority and low-priority e-mail, the sophisticated agent, just like the naive agent, chooses the HL strategy in period 1 if and only if:

$$\beta[(t+xh)(1-dh-c)-(t+xh)(dl+c)]+\alpha l \geq \beta[(t+xh)(1-dh-c)+\alpha l] \Leftrightarrow$$

$$\beta \leq \frac{\alpha l}{\alpha l+(t+xh)(dl+c)} \stackrel{\text{def}}{=} \beta_{h,l}(t).$$

Thus, the boundary between H and HL strategy choices in period 1 is the same as before. This is not the case for the agents' choice of strategy in period 0 as it depends on his or her actual actions in period 1. If (β, t) are such that $\beta \leq \beta_{h,l}(t)$ (so that the agent anticipates choosing the HL strategy in period 1 if given access to e-mail) then the agent chooses the ND strategy in period 0 if and only if:

$$\beta(t+\alpha l) \geq \beta(\alpha l+(t+xh)(1-d(l+h)-2c)) \Leftrightarrow$$

$$t \geq \frac{xh(1-d(l+h)-2c)}{d(l+h)+2c} \stackrel{\text{def}}{=} t_c.$$

If (β, t) are such that $\beta > \beta_{h,l}(t)$ (so that the agent knows that future temptation of the HL strategy will not be high enough and he or she will choose the H strategy instead), then the agent chooses the ND strategy in period 0 if and only if:

$$\beta(t+\alpha l) \geq \beta(\alpha l+(t+xh)(1-dh-c)) \Leftrightarrow$$

$$t \geq \frac{xh(1-dh-c)}{dh+c} \stackrel{\text{def}}{=} t_n.$$

The cutoff t_n is the same as for the naive agents and $t_c \leq t_n = t_0$. The regions of equilibrium strategies are shown in Figure 2.3. Figure 2.3 differs from Figure 2.2 only by a region

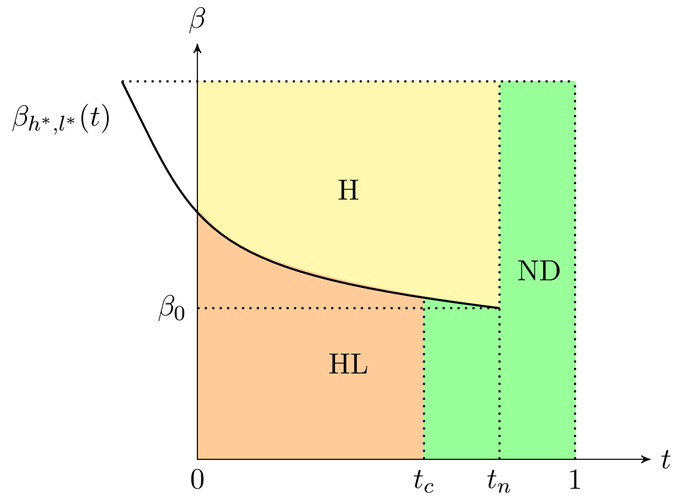

Figure 2.3: Regions of Best Response strategies for Sophisticates

between t_c, t_n and below $\beta_{h^*,l^*}(t)$, which represents agent types who use strategy ND as a commitment to prevent the choice of the HL strategy in period 1. Since naive agents anticipate to only check h-mail in the future, this commitment region is not present in Figure 2.2 and more naive agents are willing to check e-mail at period 0. Individual strategies described above lead to the following fixed point equations that characterize the equilibrium values h^* and l^*:

$$h^* = \int_0^{t_n}\int_0^1 f(\beta)\,d\beta\,dt - \int_{t_c}^{t_n}\int_0^{\beta_{h^*,l^*}(t)} f(\beta)\,d\beta\,dt,$$
$$l^* = \int_0^{t_c}\int_0^{\beta_{h^*,l^*}(t)} f(\beta)\,d\beta\,dt.$$

Simplifying, we get

$$h^* = t_n - \int_{t_c}^{t_n} F(\beta_{h^*,l^*}(t))\,dt \stackrel{\text{def}}{=} H(h^*, l^*), \tag{2.4}$$
$$l^* = \int_0^{t_c} F(\beta_{h^*,l^*}(t))\,dt \stackrel{\text{def}}{=} L(h^*, l^*). \tag{2.5}$$

Kakutani fixed point theorem establishes the existence of an equilibrium. When an equilibrium is interior, we judge its stability according to Lyapunov criteria. In the appendix we derive the following necessary and sufficient conditions for stability:

$$\left(\frac{\partial H}{\partial h} - 1\right)\left(\frac{\partial L}{\partial l} - 1\right) - \frac{\partial H}{\partial l}\frac{\partial L}{\partial h} > 0 \text{ and} \tag{2.6}$$
$$\frac{\partial H}{\partial h} + \frac{\partial L}{\partial l} - 2 < 0. \tag{2.7}$$

We use the characterization of a stable equilibrium to study how group present-bias affects the equilibrium number of people checking h-mail and l-mail in case of sophisticated employees.

2.5.2 Social Effect of Present-Bias

The following comparative statics result parallels Theorem 2.2 for naive agents. Just like before, we will focus on the stable equilibria. In the case of naive agents, we used an optimality (from the firm's point of view) criterion to select among the stable equilibria. In case of the sophisticated agents, there is no such intuitive criteria that is applicable, since it is not possible to independently characterize the equilibrium amounts of h-mail and l-mail. Therefore, our result for sophisticated agents focuses on local comparative statics around any interior stable fixed point. We show that for relatively large x, an increase in workers' present-bias leads to a higher amount of e-mail. This is the same as the result for naive agents. The difference is that in case of sophisticated agents an increase in the present-bias also leads to an increase in commitment, thus the equilibrium amount of h-mail is not constant, but decreases. A way to think about x in our model is the opportunity cost of commitment (since the productivity boost of h-mail is proportional to x). Therefore a small cost of commitment, x, will lead to a high commitment by sophisticates (decreasing both types of e-mail), which will dominate the increasing effect on l-mail due to the higher present-bias. As a result, we will see an overall decrease in the equilibrium amount of l-mail in the case of small x.

Theorem 2.5 *Let $F(\beta, a)$ be a family of distributions, parametrized by a, which represents the relative present-bias of distribution $F(\beta, a)$ and is such that $\frac{\partial F(\beta, a)}{\partial a} > 0$. Then at an interior stable equilibrium, $\frac{dh^*}{da} < 0$ whenever $\frac{dl^*}{da} > 0$, and $\frac{dl^*}{da} > 0$ as long as x is sufficiently large.*

The comparative statics result above holds only for a relatively large x. In light of our interpretation of x as the cost of commitment, this illustrates the fact that businesses became concerned with e-mail overload only after it had become universally useful. A technological advance in e-mail communication technology in the real world and in our model leads to the increased productivity of e-mail, thus to the increase of the cost of commitment (abstaining from e-mail), and therefore to larger overload problems. We have already seen that commitment of sophisticated agents to work with no distractions might potentially mitigate the decrease in output due to present-bias. In the next section we will investigate whether a firm might still benefit from restricting e-mail even in the case of sophisticated workers.

2.5.3 The Firm

When commitment is costly (large x), a firm might find that the sophistication of its employees is not enough to alleviate the productivity losses from e-mail overload. Before assessing whether or not restricting e-mail is beneficial for the firm, we re-derive the output of the firm in the case when its workers are sophisticated:

$$\begin{aligned} Y &= \int_0^{t_c}\int_0^{\beta_{h^*,l^*}(t)} f(\beta)[(t+xh^*)(1-d(h^*+l^*)-2c)]d\beta dt \\ &+ \int_0^{t_n}\int_{\beta_{h^*,l^*}(t)}^1 f(\beta)[(t+xh^*)(1-dh^*-c)]d\beta dt \\ &+ \int_{t_c}^{t_n}\int_0^{\beta_{h^*,l^*}(t)} f(\beta)td\beta dt + \int_{t_n}^1\int_0^1 f(\beta)td\beta dt. \end{aligned}$$

Simplifying and substituting values for t_c and t_n, we get:

$$\begin{aligned} Y &= -\int_0^{t_c} F(\beta_{h^*,l^*}(t))[(t+xh^*)(dl^*+c)]dt \\ &+ \int_{t_c}^{t_n} F(\beta_{h^*,l^*}(t))[t-(t+xh^*)(1-dh^*-c)]dt \\ &+ \frac{1}{2}\left(1+\frac{x^2(h^*)^2(1-c-dh^*)^2}{c+dh^*}\right). \end{aligned}$$

According to Theorem 2.5, if x is high, then the equilibrium values h^* and l^* for sophisticated present-biased agents are too low and too high, respectively, from the time consistent perspective. Just like in the case for the naive agents, we assume that the firm is not present-biased and show that if the degree of the present-bias of its employees is relatively high, it will benefit from restricting e-mail usage for the company. Again, restricting e-mail means that the firm allows only $\tau < 1$ units of time for agents to distribute between work and e-mail, and $1-\tau$ units are allocated to work by the firm.

Theorem 2.6 *If a firm introduces a policy such that $\tau \in (0,1)$ units of time is the maximum time available to employees for communication and if x is sufficiently large, then $\dfrac{\partial h}{\partial \tau} < 0$ and $\dfrac{\partial l}{\partial \tau} > 0$ at an interior stable equilibrium, and the firm will benefit from such a policy if the population of workers is sufficiently present-biased.*

For completeness we also consider the monitoring strategy (reducing e-mail parameter α) for a firm with sophisticated employees. Just like in the case with naive agents, a firm will be able to utilize this strategy only if it can distinguish the two types of e-mail. In a result parallel to Theorem 2.3 we show that a firm would benefit from such a strategy, since reducing α leads to an increase of h-mail and a decrease of l-mail, which is favorable from the point of view of a firm if the commitment cost is above some cutoff.

Theorem 2.7 $\dfrac{\partial h}{\partial \alpha} < 0$ *and* $\dfrac{\partial l}{\partial \alpha} > 0$*. Therefore, if x is sufficiently large and the population of workers is sufficiently present-biased and sophisticated, then* $\dfrac{dY}{d\alpha} < 0$*.*

The section demonstrates that compared to naives, regulation of sophisticated agents needs to take into account not just the degree of their present-bias, but also their commitment costs. The highest e-mail overload occurs when agents are both present-biased and have high commitment costs, and this is precisely when there is a role for the firm to improve output by restricting both types of e-mail or by decreasing α.

2.6 Time consistent employees

To highlight the role of agents' present-biased preferences, we now consider the case of a firm with fully time consistent employees (i.e. with $\beta = 1$, but regular discount factor $\delta \in (0,1)$). In this section, we will compare and contrast the results for time consistent agents with results for hyperbolic agents that were obtained earlier.

We begin by deriving best response strategies for time consistent agents. Given an equilibrium amount of high-priority e-mail h and low-priority e-mail l, time consistent agents will choose HL strategy in period 1 if and only if

$$\alpha l + \delta((t + hx)(1 - d(l + h) - 2c) > \delta(\alpha l + (t + xh)(1 - dh - c)) \Leftrightarrow$$

$$\delta < \frac{\alpha l}{\alpha l + (t + xh)(dl + c)} \stackrel{\text{def}}{=} \delta_1(t, l, h).$$

In period 0, an agent's strategy depends on his or her beliefs about own future action. If the agent's (δ, t) are such that $\delta \leq \delta_1(t)$, then the agent expects to only check H-mail and therefore prefers to check e-mail at all in period 0 if and only if

$$\delta^2[(t + xh)(1 - dh - c) + \alpha l] > \delta^2[t + \alpha l] \Leftrightarrow$$
$$t < \frac{xh(1 - dh - c)}{dh + c} \stackrel{\text{def}}{=} t_0.$$

On the other hand, if agent's (δ, t) are such that $\delta > \delta_1(t)$, then the agent expects to do HL strategy in period 1, and therefore checks e-mail in period 0 if and only if

$$\delta\alpha l + \delta^2(t + xh)(1 - d(l + h) - 2c) > \delta^2\alpha l + \delta^2 t \Leftrightarrow$$
$$\delta < \frac{\alpha l}{\alpha l + (t + xh)(d(l + h) + 2c) - xh} \stackrel{\text{def}}{=} \delta_0(t, l, h).$$

Notice that $\delta_0(t, l, h) < \delta_1(t, l, h)$ if and only if $t > t_0$, and $\delta_0(t_0, l, h) = \delta_1(t_0, l, h)$. Therefore, the regions of best response strategies for time consistent agents take the form in Figure 2.4. Both sophisticated and time consistent agents anticipate their future action in period 0, and therefore their cutoff for ND strategy depends on their β and δ respectively. However, time consistent agents do not use ND strategy as a commitment device, thus the commitment region found in Figure 2.3 is not present in Figure 2.4. Furthermore, sophisticated agents of all degrees of present-bias might find it optimal to use the ND strategy (if their t is high enough), while time consistent agents who are very impatient (low δ) never choose the ND strategy.

Using best response strategies defined above, we characterize equilibrium values for h^* and l^* by the following fixed-point equations:

$$h^* = 1 - \int_{t_0}^{1} \int_{\delta_0}^{1} f(\delta)\, d\delta\, dt,$$
$$l^* = \int_{0}^{t_0} \int_{0}^{\delta_1} f(\delta)\, d\delta\, dt + \int_{t_0}^{1} \int_{0}^{\delta_0} f(\delta)\, d\delta\, dt.$$

Simplifying, we get

$$h^* = t_0 + \int_{t_0}^{1} F(\delta_0(t))\, dt \stackrel{\text{def}}{=} H(h, l), \tag{2.8}$$

$$l^* = \int_{0}^{t_0} F(\delta_1(t))\, dt + \int_{t_0}^{1} F(\delta_0(t))\, dt \stackrel{\text{def}}{=} L(h, l). \tag{2.9}$$

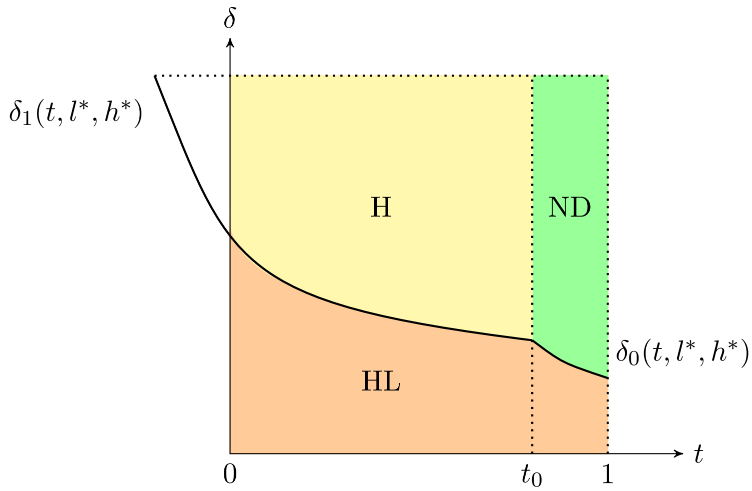

Figure 2.4: Regions of Best Response Strategies for Time Consistent agents

We proceed to analyze the comparative statics of the equilibrium with respect to changes in the level of impatience. As before, we define a population of workers with cumulative distribution of impatience $H(\delta)$ to be more patient that $G(\delta)$ if and only if $G(\delta)$ first order stochastically dominates $H(\delta)$. Compared to the case with sophisticated employees, we find that the predictions of comparative statics theorem for time consistent employees are similar for low-priority e-mail, however they are exactly opposite for high-priority e-mail.

Theorem 2.8 *Let $F(\delta, a)$ be a family of distributions, parametrized by a, which represents the relative impatience of distribution $F(\delta, a)$ and is s.t.* $\dfrac{\partial F(\delta, a)}{\partial a} > 0$. *In any stable equilibrium with time consistent employees,* $\dfrac{dh^*}{da} > 0$ *whenever* $\dfrac{dl^*}{da} > 0$, *and the latter holds in any equilibrium with a non-trivial amount of h-mail (above some small $\bar{h}$).*

The fact that $\dfrac{dl^*}{da} > 0$ has different implications for the sign of $\dfrac{dh^*}{da}$ in case of sophisticated agents and time consistent agents is an important distinction between the δ-model and the β, δ-model. However, in practice the firm cannot observe the difference between h-mail and l-mail, therefore it might be hard to empirically distinguish the two models based just on this fact. In order to get a clear qualitative difference, we look at the implication of the two assumptions on the firm's actions.

Recall that a firm with sophisticated present-biased employees finds that it is inefficient for workers to abstain from h-mail purely for commitment purposes. Thus, when the firm restricts e-mail, it simultaneously achieves two goals - reducing l-mail and reducing commitment (i.e. increase in h-mail). As before, we will find that a firm with time consistent workers (having $\alpha = 0$) prefers the smallest amount of low-priority e-mail as possible, but it might or might not view the equilibrium amount of h-mail as too high. Moreover, in the case of time consistent agents, restricting the time τ available for e-mail, will reduce both the amount of h-mail and the amount of l-mail as opposed to reducing l-mail and increasing h-mail in the case of sophisticated present-biased agents. We also find that if the importance of h-mail (or the commitment cost x) is large enough, restricting τ may actually lead to an increase in l-mail. Therefore, a firm with time consistent employees will not be as effective in remedying the problem of high amount of l-mail by restricting e-mail usage.

Theorem 2.9 *If x is sufficiently large, a policy that allows only $\tau \in (0, 1)$ units of time for employee communication will lead to a reduction in the equilibrium amount of h-mail and l-mail in a firm with time consistent employees.*

Note that unlike in the case of present-biased agents (both naive and sophisticated) we are not able to determine with certainty the overall impact of $\tau < 1$ policy for time consistent employees. The reason is that the communication via h-mail in our model produces two types of externalities and the overall sign depends in the relative magnitude of these externalities. The first one is the positive externality of increasing others' productive by engaging in h-mail. The other one is negative and is the cost that others must pay in order to read h-mail. Therefore, if costs of communication are relatively large, we can construct an example for the firm with time consistent agents such that the negative externality prevails, and the firm will benefit from a policy of restricting τ. Contrast this with the results for present-biased agents, when these two externalities were also present, but were dominated by the negative externality of the present-bias when the population of workers was sufficiently present-biased.

To summarize, in Table 2.1 we show the main effects on equilibrium amounts of h-mail and l-mail of various policies by the firm for all cases of workers' preferences. It is easy to see that if the firm is trying to reduce e-mail overload, i.e. reduce the equilibrium

Table 2.1: Summary of Results

	Naive	Sophisticated	Time consistent
Social effect of present-bias	$\frac{\partial l^*}{\partial a} > 0,\ \frac{\partial h^*}{\partial a} = 0$	$\frac{\partial l^*}{\partial a} > 0,\ \frac{\partial h^*}{\partial a} < 0$ for sufficiently large x	$\frac{\partial l^*}{\partial a} > 0,\ \frac{\partial h^*}{\partial a} > 0$ for sufficiently large h^*
Effect of reducing τ	$\frac{\partial l^*}{\partial \tau} > 0,\ \frac{\partial h^*}{\partial \tau} > 0$ if population of workers is sufficiently present-biased	$\frac{\partial l^*}{\partial \tau} > 0,\ \frac{\partial h^*}{\partial \tau} < 0$ if population of workers is sufficiently present-biased	$\frac{\partial l^*}{\partial \tau} > 0,\ \frac{\partial h^*}{\partial \tau} > 0$ for sufficiently large x
Effect of reducing α	$\frac{\partial l^*}{\partial \alpha} > 0,\ \frac{\partial h^*}{\partial \alpha} = 0$	$\frac{\partial l^*}{\partial \alpha} > 0,\ \frac{\partial h^*}{\partial \alpha} < 0$	$\frac{\partial l^*}{\partial \alpha} > 0,\ \frac{\partial h^*}{\partial \alpha} > 0$

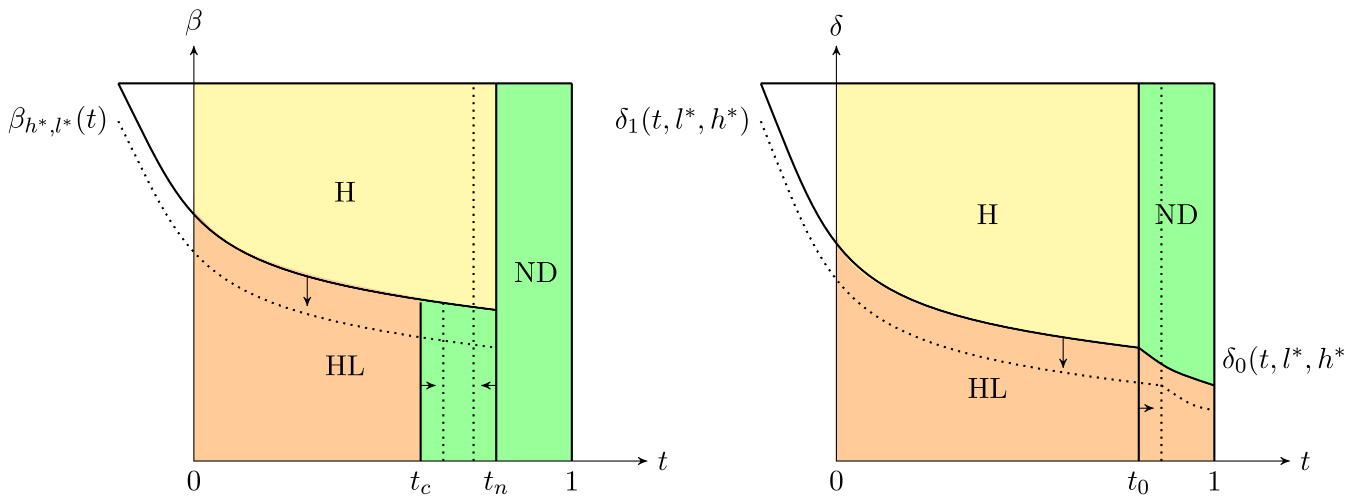

Figure 2.5: Change in the Regions of Best Response Strategies as α decreases

amount of l-mail, then as long as the degree of present-bias in the population of workers is sufficiently large, then any of the policies will be effective. By contrast, achieving the same goal with time consistent agents might be more difficult because of inevitable (and possibly undesirable) effect on the h-mail. In cases when the costs of communication are small (and therefore engaging in h-mail produces a positive externality on others), the firm will not benefit from restrictive e-mail policies. Since in practice we do observe firms implementing such strategies regardless of the size of communication costs, workers are better modeled as hyperbolic rather than time consistent agents.

Another qualitative difference between the model with present-biased agents and the model with time consistent agents is the comparative statics of the equilibrium with respect to the l-mail parameter α. If a firm is able to use a monitoring technology to differentiate between l-mail and h-mail, it will do so in case of sophisticated employees. Recall Theorem 2.7 that the effect on h-mail and l-mail had opposite signs, and thus decreasing α (via punishments) was an effective way for the firm to reduce l-mail and increase h-mail. However, in case of time consistent employees we once again find that reducing α will result in a decrease of both l-mail and h-mail.

Theorem 2.10 $\dfrac{\partial h}{\partial \alpha} > 0$ *and* $\dfrac{\partial l}{\partial \alpha} > 0$ *in an interior stable equilibrium of a firm with time consistent employees.*

The contrast in the aggregate predictions of Theorem 2.7 and Theorem 2.10 is even more apparent when considering the change in individual strategies. Consider thus a decrease in α and note which agents decide to switch strategies as a result of this change. Figure 2.5 demonstrates the effect on best response strategies of a decrease in α for sophisticates and time consistent agents. In the case of sophisticated present-biased agents (figure on the left), there are agents who switch strategies from ND to H, from ND to HL, and from HL to H. On the other hand, in case of time consistent agents (figure on the right), there are agents who switch from ND to H, from HL to ND, and from HL to H. A decrease in α pushes some time consistent agents to switch from HL to ND. By contrast, some sophisticated agents now view the HL strategy as less tempting, and therefore fewer of them decide to use ND as a commitment device, which leads to some of them actually switching in an opposite way -

from ND to HL.

Note that these are all differences in behavior, which are potentially observable (by the firm or by a researcher) without requiring any knowledge of agents' preferences. In other words, the presence of hyperbolic sophisticated agents can be revealed by observing both individual and aggregate responses to a change in the technological parameter α or the policy parameter τ.

Finally, using the β, δ-model as opposed to regular discounting gives us a natural way to model the time inconsistency of employee's preferences that seems to be present in surveys that report that agents are constantly surprised by the amount of time they end up spending on the e-mail once connected. In our model this would be modeled by the case of naive agents who in period 0 anticipate just engaging in h-mail (thus consider it to be not harmful to check e-mail), but find themselves doing both types on e-mail in period 1. Fully time consistent agents will never be surprised by their own future behavior in such a way.

2.7 Conclusion

In this paper we develop a flexible model of "e-mail overload" phenomenon, which has become a concern in many organizations and which presents somewhat of a puzzle given that the organizations are free to enact regulations that govern the use of e-mail. By assuming that there are two different types of e-mail that are potentially indistinguishable by the firm, this paper provides a possible explanation for the "e-mail overload phenomenon and evaluates different policies that can be used to alleviate the problem.

We have argued that the distracting nature of contemporary communication is a self-amplifying mechanism, which is fed by the present-bias and/or impatience of individual participants. In our model the increased productivity from high-priority communication justifies the pro-communication policies of corporations. However, an unintended consequence - inefficient distractions - occurs when individual employees are not able to commit to delaying low-priority communication until after the completion of their main task. Moreover, we show that there is a group multiplier effect, which amplifies individual suboptimal choices and leads to larger inefficiencies.

The amplification of individual present-bias in the group setting is evident in reports of the addictive nature of new communication technologies, such as e-mail, online chat, Facebook, and Twitter. Further understanding of social effects in procrastination (individual failure in prioritizing activities to partake in at a particular point in time) is important to the development of mechanisms to deal with distraction overload.

Finally, in this paper we considered several strategies for a company to deal with inefficient distractions. Since inefficiency arises from individual present-bias, the company's strategy is to attenuate its effect through either taxing the inefficient communication or providing a commitment device for completing the task. The most straightforward strategy of taxing the low-priority communication naturally improves the outcome. In cases when it is not available, the company can limit the time available for communication. Both of these strategies are preferable only for a company that faces a large present-bias among its employees.

We separately consider the case of individual preferences being present-biased (naive or sophisticated) and the case of time-consistent preferences. While some of the results in the paper hold for any specification of individual preferences, only the choice of present-biased preferences allows us to model individual failure to act according to an optimal strategy, and in the case of naive preferences, the failure to anticipate this mistake. In addition, we demonstrate that a firm with sufficiently present-biased employees will choose to implement a policy that would partially correct the e-mail inefficiency. On the other hand, the optimal regulation of a firm with time consistent employees would only depend on the size of other externalities involved in e-mail communication, and not on the degree of impatience. Furthermore, we describe testable qualitative differences in predictions for present-biased vs. time consistent agents that can be potentially observed by the firm or by a researcher.

Chapter 3

Cheap Talk with Multiple Audiences: an Experimental Analysis

3.1 Introduction

In many economic environments with communication of private information, the message sent by an informed sender may simultaneously influence the actions of many uninformed receivers with potentially conflicting interests. The financial statements of a firm, for example, are read by investors, unions, and other stakeholders; a politician's speech may be heard by constituencies with different agendas. In these cases, it is important whether the message is public (and so heard by all agents), or private (and so heard only by selected agents). As first shown by Farrell and Gibbons (1989) in a cheap talk game with one informed sender and two uninformed receivers, public communication may discipline the informed agent by inducing information transmission even when no information is sent in private; or it may make information revelation impossible even when information transmission to one of the receivers is possible in private.

Although there is a significant amount of literature that tests predictions of strategic models of communication with one sender and one receiver, there is no empirical study of communication between one sender and multiple receivers. In this paper we provide a first empirical investigation of this question by testing the predictions of Farrell and Gibbons (1989) in a controlled laboratory experiment. Following Farrell and Gibbons (1989), we start by studying communication in a simple cheap talk game: two states of the world; one informed sender who can send one of two messages after observing the state; and a receiver interested in the state who can take one of two actions after receiving the message. We then move to a similar setting with two receivers. Even when the payoffs of the receivers are independent from each other's actions (as in Farrell and Gibbons (1989)), the addition of a second receiver interferes with information transmission to the first receiver because it affects the sender's strategy. Will the sender choose a different strategy when addressing two receivers at once? Will the receivers recognize the change in the environment and update the way they interpret the sender's message? These questions cannot be answered without data on the sender's private signal, his or her message to the receivers, and the receivers' actions, and therefore are hard to address with field data. The laboratory setting helps to overcome these difficulties by allowing direct control of all the key strategic variables.

In the case of a 2-person (one-sender/one-receiver) cheap talk game, the results of our experiment are mostly in line with the previous literature. As in previous laboratory studies, we detect a tendency for the senders to reveal too much information, and for the receivers to trust the senders too much when compared to the theoretical predictions. However, the qualitative predictions of the theory are supported by the experiment: information transmission is much higher when the conflict of interest between the sender and the receiver is small. In addition, an analysis of individual behavior confirms that the *individual* players' strategies are in line with theoretical predictions: most of the senders tend to use uninformative strategies in games where there exists conflict of interest between them and their opponent, and truthfully reveal strategies otherwise; most of the receivers tend to ignore senders in games with conflict and believe their messages otherwise.

In the case of the 3-person (one sender/ two receivers), the design of the experiment is such that each game can be seen as the sum of two standard one-receiver component games that have the same sender and in which the sender's message is public. This design allows us to directly compare two-receivers games with their one-receiver components, and study the *marginal effect* of adding a second receiver. There are five possible cases, first described by Farrell and Gibbons (1989). In *one-sided discipline*, we have truthful revelation in public despite the fact that information transmission is possible with only one (but not the other) receiver in private. In *mutual discipline*, we have truthful revelation in public despite the fact that information transmission is not possible with any of the two receivers in private: in this case the conflicts of the sender with two receivers offset each other. In *subversion*, the addition of a second receiver in conflict with the sender induces no information transmission in public, despite the fact that truthful revelation is possible with the first receiver in private. In *full communication* and *no communication*, the behavior in the one receiver game is the same as in the two receivers case: in the first case, we have truthful communication both in private and in public; in the second case, no communication both in private and in public.

As in one-sender/one-receiver games, we find that information transmission is higher in one-sender/two-receivers games with a separating equilibrium than in games with only a babbling equilibrium. More interestingly, we find clear evidence that the addition of another audience alters the communication between the sender and the receiver in a way consistent with the theoretical predictions. We consider ten different scenarios: in each of the five cases mentioned above we compare the outcome of the two-receivers game with the outcome in each of the one-receiver components. In all ten scenarios, the sender changes behavior exactly according to the theory - by increasing truthful revelation in one-sided discipline and in mutual discipline cases; by reducing communication in the subversion case; and by not changing behavior in full communication and no communication cases. Similarly, in all except two of the ten comparisons, receivers modified their trust in the sender's message according to the theory.[23] All these effects are statistically significant.

We, however, find a number of deviation from the standard prediction a Nash equilibrium. There is indeed evidence that the more complex strategic interaction of a three players' game has an impact on subjects' behavior and therefore on the quality of the theoretical predictions. The sender does not seem to be affected by the higher complexity of the interaction. The amount of truthful revelation of the state is statistically higher in all

[23] Of these two, in one case the sign of the effect is correct, but not statistically significant.

games in which truthful revelation is predicted by the model, and his/her behavior does not seem to be significantly affected by the component games. The behavior of the receivers, on the contrary, seems to be affected by the component games. It appears that receivers pay more attention to their "direct relationship" with the sender, and partially ignore the other receiver. We also find that a sizable fraction of agents are consistently honest as senders and trusting as receivers. This behavior may be consistent with the hypothesis that a significant fraction of agents behave "naively" as L_0 agents in a level-k behavioral model. However, there is also evidence that a level-k model alone can not fully rationalize the data.

A study of learning in the game confirms that the deviations in behavior that we observe for the receivers are associated with the complexity of the game, and shows that they tend to disappear over time. We observe no statistically significant learning in the one-sender/one-receiver game. However, in the two-receivers game, there is statistically significant learning over time. Moreover, learning is more evident for the receivers than for the sender. Perhaps more importantly, learning is faster precisely in the games where deviations are more pronounced.

The remainder of the paper is organized as follows. In the following subsection we discuss the related literature. Section 3.2 describes the theoretical background. Section 3.3 describes the experimental design and the procedures. In Section 3.4 we discuss the results for the 2-person games, and in Section 3.5 the results for the 3-person games. In Section 3.6 we discuss deviations from equilibrium and learning. Section 3.7 concludes.

3.1.1 Related Literature

The experimental literature on cheap talk can be classified in two groups.[24] In the first group there are works that explore how cheap talk can be used to communicate intentions of play in environments with complete information.[25] In the second group the focus

[24] A survey of the experimental literature on cheap talk can be found in Crawford (1998).

[25] See, for example, Cooper et al. (1992), Forsythe et al. (1991), Guarnaschelli et al. (2000), Valley et al. (2002), Roth (1985), Palfrey and Rosenthal (1991).

is on information transmission[26] , and our paper belongs to this literature. Information transmission in classic cheap talk environments a' la Crawford and Sobel (1982) has been studied in Dickhaut et al. (1995), Blume et al. (1998), Cai and Wang (2006), Wang et al. (2010). As in Crawford and Sobel (1982), these papers study situations in which there is one informed sender and one uninformed receiver, and there is no role for communication of intentions: the sender does not choose any action that affects the receiver's utility directly. Dickhaut et al. (1995) show that the key qualitative predictions of Crawford and Sobel (1982) are supported in the laboratory: notably, information transmission is higher when the degree of conflict is smaller. In a model with repeated anonymous interactions, Blume et al. (1998) show that informative communication emerges endogenously even when there is no common language (i.e. only symbols without an intrinsic meaning can be used by the sender). Cai and Wang (2006) and Wang et al. (2010) also confirm Crawford and Sobel's main qualitative results, but they highlight a systematic tendency for senders to reveal more information than predicted in equilibrium.

Our paper departs from this literature by comparing the baseline case with one receiver to the case with multiple receivers. To our knowledge it is the first (and so far the only) paper to study the effect of public communication with multiple receivers in a laboratory experiment. The literature on multiple audiences has been exclusively theoretical. Farrell and Gibbons (1989) in their seminal paper consider the same environment that we study in our experiment. In a recent theoretical contribution, Goltsman and Pavlov (2010) have generalized the key insights of Farrell and Gibbons (1989) in an environment with a continuum of states and actions.

Palfrey and Rosenthal (1991) and Guarnaschelli et al. (2000) also study preplay communication in games with asymmetric information and more than two agents. In these works, therefore, each player is a sender and each message is heard by more than one receiver (the other players). This literature, however, is substantially different from our work for two reasons. First, these papers do not study the differences between private and public communication. Second, and most importantly, in this work the receiver's payoff is directly

[26]Guarnaschelli et al. (2000), Valley et al. (2002), Palfrey and Rosenthal (1991) study preplay communication in games with asymmetric information, so these papers belong to both groups.

Table 3.1: 2-person matrix game payoff

Sender's payoff

	Heads	Tails
Action A	v_1	0
Action B	0	v_2

Receiver's payoff

	Heads	Tails
Action A	x_1	0
Action B	0	x_2

affected by the sender's actions: so communication of intentions of play and of information are not separated.

3.2 Theoretical Background

We adopt the same model of cheap talk used in Farrell and Gibbons (1989). In this model, there are two states of the world H, T. Nature chooses state H with the probability π and only one agent, the sender, is informed of the choice. After having observed the state, the sender selects a message (Heads or Tails) to send to the other players, the receivers, via a costless and a non-verifiable claim, i.e. cheap talk. Each receiver then takes an action (Action A or Action B) and the payoffs are realized. The payoff of each receiver depends only on the state and the action that he or she has chosen. The payoff of the sender depends on the state and the actions of all receivers.

We consider two basic treatments. In the 2-person game, there is only one receiver. The payoffs in this case can be described as in Table 3.1. For example, if the state is Heads and the receiver chooses action A, then the sender receives v_1 and the receiver receives x_1; if the sender chooses B, then both players receive 0. In all treatments we assume $x_1 > 0, x_2 > 0$. When both v_1 and v_2 are positive, then the players have the same ordinal preference over the actions in both states; in all the other cases there is a state in which the the sender and the receiver would choose different actions.

Table 3.2: 3-person matrix game payoff

Sender's payoff

	Heads	Tails
Action A1	v_1	0
Action B1	0	v_2

Sender's payoff

	Heads	Tails
Action A2	w_1	0
Action B2	0	w_2

Receiver 1's payoff

	Heads	Tails
Action A1	x_1	0
Action B1	0	x_2

Receiver 2's payoff

	Heads	Tails
Action A2	y_1	0
Action B2	0	y_2

In the 3-person game there are two receivers. The payoff of the sender in this case is the sum of two components: the first depends only on the state and the action of receiver 1; the second component depends only on the state and the action of receiver 2. Table 3.2 represents the payoffs in this case. For example, if the state is Heads and receiver 1 chooses A1 and receiver 2 chooses A2, then receiver 1 obtains x_1, receiver 2 obtains y_1 and the sender obtains v_1+w_1. In all treatments, we will assume $x_1 > 0, x_2 > 0$ and $y_1 > 0, y_2 > 0$. When both $v_1 + w_1$ and $v_2 + w_2$ are non negative, then the players have the same ordinal preference over the actions in both states; in all the other cases there is a state in which the the senders and at least one receiver would choose different actions.

In these games we can have two types of pure strategy equilibria. In the first type, the sender's message is uninformative and therefore is ignored by the receivers in equilibrium. Each receiver in such equilibrium chooses the action based on the prior only: $a_{pool} = A$ if $\pi x_1 \geq (1-\pi)x_2$, and $a_{pool} = B$ otherwise. This equilibrium always exists for any choice of parameters. We will refer to it as a *pooling equilibrium.* In the second type, the sender's message fully reveals the state. If we denote $m(s)$ the message sent in state s, and $\mu(s;m(s))$ the posterior probability of receiver i on state s in state s, we have $\mu(s;m(s)) = 1$. We will refer to this type of equilibrium as a *separating equilibrium.* It is easy to see that a separating equilibrium does not always exist. In a 2-person game a fully revealing equilibrium exists if and only if $v_1 > 0$ and $v_2 > 0$. In a 3-person game, a fully revealing equilibrium exists if and only if $v_1 + w_1 \geq 0$ and $v_2 + w_2 \geq 0$.

Comparing Table 3.1 and Table 3.2 it can be verified that a 3-person game can be seen as the sum of two 2-player games (one with receiver 1 and one with receiver 2) with the same Sender and in which the Sender is forced to make a public message heard by both. This design allows us to directly compare two-receivers games with their one-receiver components, and study the *marginal effect* of adding a second receiver. In the following we will call the "component games" of a 3-player game the two games that are defined by the 3-player game when one of the two receivers is eliminated.

From the conditions discussed above, it follows that if a separating equilibrium exists with both receivers in the component games, then it must exist in public setting as well. The converse does not hold. The five cases that may arise have been described in the introduction and are summarized here in Table 3.3.[27] Specific numerical examples will be presented in Section 3.3 where we discuss the treatments of the experiment.

Table 3.3: Types of private vs. public communication

	Separating Equilibrium in **private**	Separating Equilibrium in **public**
No Communication	No	No
Full Communication	Yes, with both receivers	Yes
One-Sided Discipline	Only with one receiver	Yes
Mutual Discipline	No	Yes
Subversion	Only with one receiver	No

On the basis of this discussion, we can organize the theoretical predictions of the model in two groups. First we have the predictions concerning how behavior depends on the degree of conflict in the game. The games, both 2-person and 3-person, can be classified in *conflict games*, where the unique equilibrium is pooling, and *no conflict games*, where there is a separating equilibrium. We have:

Hypothesis 1. *Both in 2-person and in 3-person games, the sender's strategy is less informative in games of conflict than in games of no conflict. Similarly, the receivers' actions are more correlated to the sender's message in games of no conflict than in games of conflict.*

[27]See Farrell and Gibbons (1989) for a formal derivation.

Hypothesis 1 is a natural extension of the hypotheses tested in previous laboratory experiments of cheap talk games described in Section 3.1.1. With respect to this literature, here we extend the analysis by considering the case in which there may be more than one receiver. In the presence of multiple receivers the conflict depends on the 3 ways strategic interaction of the players.

Second, we can test how behavior changes as we move from a private setting with one receiver to a public setting with two receivers. We say that adding a second receiver has a *positive effect* if the sender increases the informativeness of his strategy, and receiver 1 increases the correlation of his action with the message. The effect is *negative* if the sender reduces the informativeness of his strategy and receiver 1 reduces the correlation of his action with the message; and it is *neutral* if the sender's and the receivers' strategies remain unchanged. The setup presented above leads us to the following Hypothesis:

Hypothesis 2. *Adding a second receiver to a 2-person game has a positive effect in games of One-Sided Discipline and Mutual Discipline, a negative effect in a game of Subversion, and a neutral effect in games of No Communication and Full Communication.*

Hypothesis 2 constitutes a direct test of the ability of the model to predict the marginal effect on information transmission of a second receiver. Note that in the statement of Hypothesis 2 (and in Table 3.3) we keep receiver 1 as our reference point and consider receiver 2 as the additional player. A statement similar (and equivalent) to Hypothesis 2 can be made taking receiver 2 the reference.

3.3 Experimental Design and Procedures

The experiment was conducted in the Princeton Laboratory for Experimental Social Science (PLESS) and programmed using z-Tree software (Fischbacher (2007)). We ran 6 sessions with a total of 72 subjects. All participants were registered students at Princeton University and had been recruited by e-mail. No subject participated in more than one session, and each session contained exactly 12 subjects. The typical experimental session lasted about 1.5 hours. During the experiment, participants accumulated "points," which were exchanged for dollars at a pre-specified rate.[28] Including the \$10 show-up fee, the total earnings for the experiment ranged from \$24.80 – \$33.80.

Each session consisted of two parts. In the first part, participants were divided into pairs and played the game with one sender and one receiver for 18 periods. Table 3.4 presents 6 games, each of which was repeated 3 times in a random sequence of 18 games.[29] Each period subjects were randomly assigned to a group and given a role of a sender or of a receiver, so that the composition of groups and the roles changed every period. At the start of each period participants were informed of their role and the game that was to be played with their opponent. In addition, senders observed the state of the world and were asked to send a message (Heads or Tails) to their partner. Then receivers saw the message and chose their actions. At the end of each round, all participants viewed a summary screen that contained the state, the message, the action and their individual payoff for the round. The main purpose of Part I of the experiment was to familiarize the participants with the cheap talk game and get the baseline of the communication strategies in private setting.

Part II of each session was a test of cheap talk game with two receivers. Subjects were divided into groups of three, and each of the 4 groups had one sender and two receivers. Just like in Part I, the participants were re-matched and assigned roles at random each period. The 5 different games that were played in this round correspond to the five types of public communication described above and are presented in Table 3.5 .[30] Each of these games was repeated 4 times for a total of 20 periods in Part II. Note that each of the 5 games is constructed by combining two games from Part I to allow for a direct comparison of private and public settings. Rounds in Part II were similar to rounds in Part I, i.e. only senders had information about the state of the world, which they had an opportunity to share with the receivers via a cheap talk message. The message had to be the same and was sent simultaneously to both receivers. Finally, each receiver took an action and the summary for the round was reported to all subjects. The total earning of the participants

[28]In all of the sessions 25 points were equal to \$1.00

[29]Note that the payoffs of Table 3.4 are an affine transformation of the payoffs described in Table 3.1. We chose this (equivalent) way of represent the game in the experiment to avoid negative payoffs.

[30]Similarly as for the 2-person games, the payoffs of Table 3.4 are an affine transformation of the corresponding payoffs described in Table 3.2 to avoid negative payoffs.

Table 3.4: 2-person games

Game 1:

Sender's payoff

	Heads	Tails
Action A	10	0
Action B	0	10

Receiver's payoff

	Heads	Tails
Action A	10	0
Action B	0	10

Game 2:

Sender's payoff

	Heads	Tails
Action A	25	0
Action B	0	25

Receiver's payoff

	Heads	Tails
Action A	10	0
Action B	0	10

Game 3:

Sender's payoff

	Heads	Tails
Action A	15	0
Action B	0	15

Receiver's payoff

	Heads	Tails
Action A	0	15
Action B	15	0

Game 4:

Sender's payoff

	Heads	Tails
Action A	20	0
Action B	0	20

Receiver's payoff

	Heads	Tails
Action A	0	20
Action B	20	0

Game 5:

Sender's payoff

	Heads	Tails
Action A	0	10
Action B	10	30

Receiver's payoff

	Heads	Tails
Action A	10	0
Action B	0	10

Game 6:

Sender's payoff

	Heads	Tails
Action A	30	10
Action B	10	0

Receiver's payoff

	Heads	Tails
Action A	10	0
Action B	0	10

for Part I and Part II were a sum of the show-up fee and their earnings in each of the periods.

Table 3.5: 3-person games

Game 12 - Full Communication

Sender's payoff

	Heads	Tails
Action A1	10	0
Action B1	0	10

Sender's payoff

	Heads	Tails
Action A2	25	0
Action B2	0	25

Receiver 1's payoff

	Heads	Tails
Action A1	10	0
Action B1	0	10

Receiver 2's payoff

	Heads	Tails
Action A2	10	0
Action B2	0	10

Game 13 - Subversion

Sender's payoff

	Heads	Tails
Action A1	10	0
Action B1	0	10

Sender's payoff

	Heads	Tails
Action A2	15	0
Action B2	0	15

Receiver 1's payoff

	Heads	Tails
Action A1	10	0
Action B1	0	10

Receiver 2's payoff

	Heads	Tails
Action A2	0	15
Action B2	15	0

Continued on next page

Game 23 - One-Sided Discipline

Sender's payoff		
	Heads	Tails
Action A1	25	0
Action B1	0	25

Sender's payoff		
	Heads	Tails
Action A2	15	0
Action B2	0	15

Receiver 1's payoff		
	Heads	Tails
Action A1	10	0
Action B1	0	10

Receiver 2's payoff		
	Heads	Tails
Action A2	0	15
Action B2	15	0

Game 56 - Mutual Discipline

Sender's payoff		
	Heads	Tails
Action A1	0	10
Action B1	10	30

Sender's payoff		
	Heads	Tails
Action A2	30	10
Action B2	10	0

Receiver 1's payoff		
	Heads	Tails
Action A1	10	0
Action B1	0	10

Receiver 2's payoff		
	Heads	Tails
Action A2	10	0
Action B2	0	10

Continued on next page

Game 34 - No Communication

Sender's payoff		
	Heads	Tails
Action A1	15	0
Action B1	0	15

Sender's payoff		
	Heads	Tails
Action A2	20	0
Action B2	0	20

Receiver 1's payoff		
	Heads	Tails
Action A1	0	15
Action B1	15	0

Receiver 2's payoff		
	Heads	Tails
Action A2	0	20
Action B2	20	0

3.4 Two person games

We analyze the experimental results in three subsections. In this section, we analyze the decisions in the 2-person games. We then analyze the decisions in 3-person games in Section 3.5. Finally, in Section 3.6 we discuss in detail the deviations from the theoretical equilibrium and the learning effects.

In order to describe senders' and receivers' strategies in the experiment, we construct two variables. The variable for the sender is called *telling_truth* and it is equal to 1 for a particular sender if the sender's message coincides with the state, and it is equal to 0 otherwise. The variable for the receiver is called *believing_sender* and is equal to 1 if the receiver's action is equal to the action that would be optimal if senders' message was in fact the true state, and 0 otherwise. *Telling_truth* is designed to capture the informativeness of the sender's message strategy: if the sender is using a truthful strategy, the variable should be one; if the sender is uninformative it should be equal to 1/2.[31] Similarly,

[31] There may be a separating equilibrium in which the sender systematically reports the opposite of the true state. We will ignore this case, and there is no evidence in the experiment of these strategies.

believing_sender is designed to describe the receiver's posterior beliefs: in fully revealing equilibria, we should expect it to be equal to one; in an uninformative equilibrium, it should be 1/2.[32]

In Table 3.6 we aggregate data for games of no conflict (games 1 and 2) and for games of conflict (games 3, 4, 5, and 6) and report the mean and the standard deviation for *telling_truth* and *believing_sender*. Theoretical values are presented in parentheses. Using the unpaired t-test we conclude that both senders' and receivers' strategies differ in games of no conflict and in games of conflict at 1% significance level (p-values = 0.000). In particular, senders pass more information to the receivers when their incentives are aligned, and receiver trust senders more in games of no conflict. Table 3.7 lets us take a closer look at strategies in different games of no conflict and in games of conflict. Senders' behavior is clearly in line with the theoretical prediction in games 1,2, and 5. Some aversion to lying, however is present in games 3, 4, and 6: H_0 : *telling_truth* $= .5$ is rejected with p-value 0.0000 for game 3, with p-value 0.0009 for game 4, and and with p-value 0.0002 for game 6. This phenomenon is in line with the findings of the previous literature on simple one-sender/one-receiver cheap talk reviewed in Section 3.1.1. Receivers do not appear to trust senders more (or less) than they should in games 1,2,3, and 4.[33] This is evident in games 1 and 2. In games 3 and 4: H_0 : *believing_sender* $= .5$ is not rejected with p-value 0.1791 for games 3 and 4. There is however evidence for credulity in games 5 and 6: in both cases, we reject H_0 : *believing_sender* $= .5$ with p-value 0.000. The credulity bias we observe in the receivers' strategies is also consistent the findings in the literature of simple one sender-one receiver games, though less apparent than reported in this literature.[34]

The simple design of our experiment allows us to have a look at how individual strategies

[32]Here too we can have separating equilibria in which the receiver systematically chooses the opposite of the strategy recommended by the sender. We will ignore this case, and there is no evidence in the experiment of these strategies.

[33]Across the 6 sessions that were conducted, the mean of *believing_sender* variable varies from 0.944 to 1.000 in game 1, from 0.889 to 1.000 in game 2, from 0.444 to 0.722 in game 3, from 0.500 to 0.667 in game 4, from 0.722 to 0.944 in game 5, and from 0.722 to 1.000 in game 6. The fact that the means in Table 3.7 are the same for games 1 and 2, games 3 and 4, and games 5 and 6 is purely by chance.

[34]A bias for credulity is observed in Cai and Wang (2006). The difference with their findings is probably due to the fact that our setting is simpler than the their setting, where a finite number of states (larger than two) is assumed.

Table 3.6: Two person games - summaries of the means

	telling_truth		believing_sender	
	mean	sd	mean	sd
No conflict	0.972 (1.0)	0.165	0.981 (1.0)	0.135
Conflict	0.627 (0.5)	0.484	0.708 (0.5)	0.455

Table 3.7: Two person games - means by game

	telling_truth		believing_sender	
Game	mean	sd	mean	sd
1	0.981 (1.0)	0.135	0.981 (1.0)	0.135
2	0.963 (1.0)	0.190	0.981 (1.0)	0.135
3	0.741 (0.5)	0.440	0.565 (0.5)	0.498
4	0.657 (0.5)	0.477	0.565 (0.5)	0.498
5	0.435 (0.5)	0.498	0.852 (0.5)	0.357
6	0.676 (0.5)	0.470	0.852 (0.5)	0.357

Table 3.8: Two person games - comparisons by game

telling_truth

	1	2	3	4	5	6
1		0.4100	0	0	0	0
2			0	0	0	0
3				0.1835	0	0.2969
4					0.0010	0.7741
5						0.0003
6						

believing_sender

	1	2	3	4	5	6
1		1	0	0	0.0005	0.0005
2			0	0	0.0005	0.0005
3				1	0	0
4					0	0
5						1
6						

conform to the theoretical predictions. For each participant we gather information about their strategies in all rounds, then in Table 3.9 classify their strategies as a sender as "Truth," "Mix," or "Lie," depending on how often they tell the truth in games of conflict and of no conflict.[35] Similarly, we classify their strategies as a receiver as "Trust," "Mix," or "Deny"[36] in games of no conflict and in games of conflict. For example, an agent counted in the third sub-column ("Lie") of the first column ("Truth") is telling the truth with more than 80% probability in no conflict games, and with less than 20% probability in conflict games. According to the theory, in games of no conflict we should see that everybody is telling the truth and believing their partner, and in games of conflict everybody should mix. Thus, we expect all participants to be classified in the cell highlighted in bold. The evidence is obviously not as clear cut as the theoretical prediction, but we still find that most subjects choose strategies correctly according to this guideline: 69.4% of the senders, and 65.3% of the receivers. Because the majority of the deviations are in the "Truth-Truth" columns, Table 3.9 also provides another illustration of the fact that senders have a tendency to reveal the truth too frequently and the receivers tend to trust senders too much. On the other hand, we find little evidence that there are systematic liars and we will discuss possible explanations of this in Section 3.6.2.

Despite theoretical predictions that all games of conflict have a unique pooling equilibrium, experimentally we find that not all games of conflict are the same. Table 3.8 presents p-values from the unpaired t-tests of equilibrium strategy comparisons for each pair of games and demonstrates that receivers choose different strategies in games 3&4 and games 5&6. For example, the fact that the cell in column 2, row 1 is large (0.4100) implies that the null hypotheses that in games 1 and 2 *telling_truth* is the same cannot be rejected with high confidence. On the other hand, the fact that the cell of column 4, row 2 is small (zero) signifies that the null hypothesis that *telling_truth* is the same in games 4 and 2 is rejected with high confidence. The difference between games 3&4 and 5&6 could possibly be attributed

[35] A sender is classified as a "Truth," "Mix," or "Lie" type if *telling_truth* is equal to 1 for, respectively, 80% or more, 20% to 80%, or 20% or less of the time. These results are robust to using 30-70 and 40-60 cutoffs. A similar approach is used in Battaglini et al. (2010) and Cai and Wang (2006). In a more complicated game, Wang et al. (2010) use MLE to estimate the level-k model types.

[36] We use the same probability ranges as for the senders' strategies.

Table 3.9: Two person games - individual strategy profiles (out of the total of 72 subjects)

telling_truth

No Conflict	Truth			Mix			Lie		
Conflict	Truth	Mix	Lie	Truth	Mix	Lie	Truth	Mix	Lie
	16.7%	**69.4%**	5.6%	2.8%	5.6%	0	0	0	0

believing_sender

No Conflict	Trust			Mix			Deny		
Conflict	Trust	Mix	Deny	Trust	Mix	Deny	Trust	Mix	Deny
	27.8%	**65.3%**	1.4%	4.2%	1.4%	0	0	0	0

to the fact that the conflict is not as apparent in games 5&6 as it is in games 3&4. In games 5&6 receivers see that the conflict is only in one of the states, thus they may tend to believe the senders a lot more than in games 3 and 4. Moreover, from Table 3.8 we see that senders choose different strategies in games 3&4&6 and in game 5. While there is slight aversion to lying in game 6 (and in games 3&4), there is none in game 5. The difference between game 5 and game 6 could potentially be explained by subjects' lack of strategic sophistication. If subjects are pressed for time, or just inattentive, and only check whether or not there is conflict in the first state of the world (Heads), game 5 will look to them as a game of conflict while game 6 will look like a game of no conflict. Overall, we conclude that games 5 and 6 are cognitively more complicated compared to games 3 and 4, since in them it is not enough to just look at one of the states to determine whether or not this is a game of conflict. We will develop this issue further in Section 3.6 after discussing the results for 3-person games, where the lack of strategic sophistication is perhaps more evident.

3.5 Three person games

For the cheap talk games with two receivers we define the *telling_truth* variable for the sender as in the previous section. Receivers' actions are now described by two separate variables: *believing_sender1* and *believing_sender2* for receiver 1 and receiver 2 respectively. The

Table 3.10: Three person games - summaries of the means

	telling_truth		**believing_sender1**		**believing_sender2**	
	mean	sd	mean	sd	mean	sd
No conflict	0.962 (1.0)	0.192	0.976 (1.0)	0.154	0.917 (1.0)	0.277
Conflict	0.682 (0.5)	0.467	0.656 (0.5)	0.476	0.693 (0.5)	0.463

Table 3.11: Three person games - means by game

	telling_truth		**rbelieving_sender1**		**believing_sender2**	
Game	mean	sd	mean	sd	mean	sd
12	1.000 (1.0)	0.000	0.990 (1.0)	0.102	0.979 (1.0)	0.144
13	0.740 (0.5)	0.441	0.781 (0.5)	0.416	0.729 (0.5)	0.447
23	0.927 (1.0)	0.261	0.979 (1.0)	0.144	0.854 (1.0)	0.355
34	0.625 (0.5)	0.487	0.531 (0.5)	0.502	0.656 (0.5)	0.477
56	0.958 (1.0)	0.201	0.958 (1.0)	0.201	0.917 (1.0)	0.278

conflict in the overall game is defined as before, i.e. whether or not there is a separating equilibrium for the sender: games 13 and 34 are games of conflict in which there is no informative equilibrium; while games 12, 23, and 56 are games of no conflict where there is an equilibrium where the sender fully reveals the state. Note that it is important to distinguish the roles of receiver 1 and receiver 2 because the games are not symmetric with respect to them. For example, according to the theory, in game 23 the sender is supposed to be truthful, and the receivers are supposed to believe him/her. For receiver 1 believing is optimal in game 2 (in which he is the only receiver), so believing is optimal even if receiver 2 is ignored. On the other hand, for receiver 2, believing is not an equilibrium in game 3 (where receiver 1 is not playing).

In the next two subsections we first present how equilibrium behavior in the 3 players' game changes when a separating equilibrium exists and when it does not; then we study the marginal effect of having a second receiver using the 2 players game as a benchmark.

3.5.1 Conflict and information revelation

The first column of Table 3.10 provides information on how the sender reacts to conflict in the 3-person games by aggregating the data in games with no conflict in which the theory predicts *telling_truth* $= 1$ and in games of conflict, in which the theory predicts *telling_truth* $= 1/2$. It is clear that the amount of truth telling is higher in the first class of games than in the second.[37] As an example, consider the mutual discipline game 56. In this case the sender is not supposed to report truthfully in private, that is in game 5 or in game 6. Indeed we find (Table 3.7), the expected value of *telling_truth* is 0.435 and 0.676 in games 5 and 6 respectively. When the message is public, and the sender is playing in the combined game 56 and truthful revelation is optimal: indeed *telling_truth* in game 56 is 0.958. The breakdown of senders' mean strategies by game in Table 3.11 confirms this conclusion: senders reveal more information in the no conflict games, and the difference is statistically significant in all cases. Only in game 13 does the sender appear to report truthfully more than is predicted by the theory.

The results for the receivers are not as sharp as for the senders, but they provide the same conclusions. The second and third columns of Table 3.10 show that *believing_sender1* and *believing_sender1* are significantly higher in no conflict games than in conflict games.[38] Both receiver 1's and receiver 2's behavior appears to be consistent with equilibrium predictions in all games.

The results that emerge in the analysis of aggregate data are confirmed by the individual data. In Table 3.12 we classify each participant in terms of which strategies they use in each of the roles (sender, receiver 1, and receiver 2) and each type of the game (no conflict and conflict).[39] The games with two receivers appear to be cognitively more complicated than the games with only one receiver: this can be seen by the fact that players are more uniformly dispersed across the possible strategy profiles, a sign of the fact that players are behaving less according to the theory. Nevertheless, the equilibrium prediction is the mode

[37]Unpaired t-tests that compare the strategies in games of conflict vs. games of no conflict give p-values of 0.0000.

[38]Unpaired t-tests that compare the strategies in games of conflict vs. games of no conflict give p-values of 0.0000.

[39]Again, we use 100-81%, 80-21% and 20-0% percentage intervals for classification. These results are robust to using 30-70 and 40-60 cutoffs.

Table 3.12: Three person games - individual strategy profiles

telling_truth

No Conflict	Truth			Mix			Lie		
Conflict	Truth	Mix	Lie	Truth	Mix	Lie	Truth	Mix	Lie
	36.1%	**43.1%**	11.1%	2.8%	5.6%	1.4%	0	0	0

% out of the total of 72 subjects

believing_sender1

No Conflict	Trust			Mix			Deny		
Conflict	Trust	Mix	Deny	Trust	Mix	Deny	Trust	Mix	Deny
	34.7%	**44.4%**	12.5%	2.8%	4.2%	0	1.4%	0	0

% out of the total of 72 subjects

believing_sender2

No Conflict	Trust			Mix			Deny		
Conflict	Trust	Mix	Deny	Trust	Mix	Deny	Trust	Mix	Deny
	33.3%	**36.1%**	12.5%	5.6%	9.7%	2.8%	0	0	0

% out of the total of 72 subjects

of the distribution of players across strategy profiles for all players (43.1% for the sender, 44.4% for receiver 1, and 36.1% for receiver 2). In summary, we find significant support in the data for Hypothesis 1 for both 2-person and 3-person games. On the other hand, the results for 3-person games are in contrast with the 2-player games, as we find much less evidence of excessive truthfulness in senders' strategies and credulity in receivers' strategies in the former class of games than we do in the latter.

3.5.2 The marginal effects of a second receiver

We now turn to the main question of the paper – what is the effect of a second receiver on a cheap talk communication? We can breakdown this question in two parts. First, does the sender's strategy change according to the theoretical prediction? Second, do receivers recognize that the sender's strategy has changed and change their behavior accordingly?

The first quadrant in Table 3.13 addresses the first question. The values in the table show the difference between the mean strategies in 3-person games and 2-person games. The rows in Table 3.13 correspond to the benchmark 2-person games and columns are the additional audience added to obtain a 3-person game. For example, the entry in the second row and third column is the difference between *telling_truth* in the 23 game and in the 2 game. The model predicts no difference in behavior, and indeed the difference reported is small and not statistically significant. On the contrary, the model predicts *telling_truth*= 1 in game 1 and *telling_truth*= 1/2 in game 13. The extent to which this prediction is supported by the data can be verified by inspecting the entry in row 1 and column 3: as predicted, this entry is negative and statistically significant. Following a similar logic, we can interpret all the other ten values, that correspond to the ten possible marginal effects. When observed marginal effects are consistent with the theory, we write them in bold in Table 3.13. In all cases the results are consistent with the predictions. When behavior is different, the entries are different with the correct sign and statistically significant. When behavior is predicted to be the same, the differences in the entries are not statistically significant.

A similar analysis can be done for *believing_sender*. Of the ten possible cases, all but

Table 3.13: Comparison between 2-person games and 3-person games

Telling_truth

	1	2	3	4	5	6
1	-	**0.0185**	$-$ **0.2419****	-	-	-
2	**0.0370**	-	$-$**0.0359**	-	-	-
3	$-$**0.0012**	**0.1863****	-	$-$**0.1157**	-	-
4	-	-	$-$**0.0324**	-	-	-
5	-	-	-	-	-	**0.5231****
6	-	-	-	-	**0.2824****	-

Believing_sender

	1	2	3	4	5	6
1	-	**0.0081**	$-$**0.2002****	-	-	-
2	$-$**0.0023**	-	$-$**0.0023**	-	-	-
3	0.1644*	**0.2894****	-	$-$**0.0336**	-	-
4	-	-	**0.0914**	-	-	-
5	-	-	-	-	-	**0.1065***
6	-	-	-	-	0.0648	-

** p<0.01, * p<0.05

Results in bold are consistent with the theoretical predictions. Results not in bold are either statistically insignificant, or have a sign opposite of the theoretical prediction.

two are fully in line with the theoretical predictions. The theory predicts a statistically significant positive difference between *believing_sender2* in game 56 (*believing_sender2* $= 1$) and in game 6 (*believing_sender2* $= 1/2$). The difference in the entry of row 6 and column 5 has the correct positive sign, but this difference is not statistically significant at conventional levels.[40] The second case that departs from the theoretical predictions is the comparison between game 13 and game 3. According to theory, there should be no difference in strategies as both game are games of conflict. Nevertheless, we find that receiver 2 believes the sender more in game 13 than in game 3. The difference, however, is significant only at 5% level, but not at 1% level.

In summary, we find significant support in the data for Hypothesis 2. The evidence is in line with theoretical predictions in all of the ten cases for senders, and in eight over ten cases for receivers.

3.6 Deviations from equilibrium and learning

The discussion of the previous section shows that the comparative statics of the model is supported by the data. Still, there are a number of points of divergence in the data from the theory. When compared to Table 3.9, Table 3.12 makes it clear that subjects' behavior is more dispersed in the 3-person games. This suggests that players find it harder to play it. This is not, perhaps, a surprising observation, since the 3-person games are considerably more sophisticated from a strategic point of view. Although the evidence presented in Section 3.5.2 makes clear that players are strategic and internalize the presence of the second receiver, it is still possible to conjecture that they only partially internalize the strategic implications of the second receiver. Three sets of questions, therefore, seem relevant. First, do players underestimate the impact of the second receiver, and focus too much on their "direct" relationship with the sender? Second, to what extent are the players really strategic? And finally, do subjects tend to learn over time or do their mistakes persist over time? In what follows, we address these questions in detail.

[40] It is significant at 15.3% level.

3.6.1 Complexity of the game and strategic behavior

To address the first set of questions we study how the deviations from equilibrium behavior depend on the type of game that is played. In each game j, the variables *mistake_of_receiver_i* and *mistake_of_sender* measure the deviations from theoretical equilibrium: the first is the absolute value of the difference between the equilibrium probability of believing the sender and the empirical frequency of *believing_sender* in game j; the second is the absolute value of the difference between the equilibrium probability of revealing the true state, and the empirical frequency of *telling_truth* in game j. Table 3.19 presents a regression where these measures of mistakes are regressed against a number of variables describing the characteristics of the game. Start by considering the last column ("all games"). The two regressions described in this column use data from both 2-person and 3-person games. *Conflict* is a dummy variable equal to one if it refers to a game of conflict; *3-person game* is a dummy equal to one if the game has 2 receivers; *period* is a control variable measuring the period. The clear finding is that players tend to make more mistakes in games of conflict than in games without conflict: for the sender and the receivers it is significantly positive at a 1% level. This suggests that games of conflict are more difficult to play than games without conflict. This is not surprising, since games of no conflict have equilibria in pure strategies, while in games of conflict equilibria are in mixed strategies. The second clear result is that receivers find 3-person games harder to play than 2-person games (the variable *3-person game* is positive and significant at a 1% level). Senders, on the contrary, do not seem to be affected by the numbers of receivers: for them the variable is not significant. The first and second columns of Table 3.19 focus on 2-person games and 3-person games and confirm the effect of the variable conflict described above.[41]

To further understand the relationship between mistakes and the complexity of the game, we introduce a variable that measures the complexity of game for two receivers, cog_i: it is 1 for receiver i if the conflict in the individual component game is different from the overall game. For example, game 13 is cognitively complicated for receiver 1, because he or she needs to consider *both* his own and receiver 2's component games: game 1 is a game

[41]We will comment on the effect of the other control variables (*period*, *conflict experience*, and *experience as a sender*) in the next section, where we discuss learning effects.

Table 3.14: Behavioral predictions of the level-k model for 2-person games

	Games 1&2		Games 3&4		Game 5		Game 6	
	Sender	Receiver	Sender	Receiver	Sender	Receiver	Sender	Receiver
$L0$	Truth	Trust	Truth	Trust	Truth	Trust	Truth	Trust
$L1$	Truth	Trust	Lie	Deny	"Tails"	Mix	"Heads"	Mix
$L2$	Truth	Trust	Truth	Trust	Mix	Mix	'Mix	Mix
$L3$	Truth	Trust	Lie	Deny	Mix	Mix	Mix	Mix
$L4$			Truth	Trust	Mix	Mix	Mix	Mix
...	...	...	...	...	...	...	...	...
$L\infty$	Truth	Trust	...	...	Mix	Mix	Mix	Mix
NE	Truth	Trust	Mix	Mix	Mix	Mix	Mix	Mix

of no conflict while the overall game 13 is a conflict game. In column (1) of Table 3.20 we report the result of a regression analysis where *mistake_of_receiver_i* is explained as a function of cog_i and other controls. Note that cog_2 is always significant for the sender and for receiver 2. This analysis also shows that after controlling for the period of the game, and the level of experience in more complicated games, the variable is significant for receiver 1 as well.[42] We can therefore conclude that there is evidence that players find the 2-receivers game more complicated to play, and that this complication is more pronounced in games that are in fact more complicated, i.e. with $cog_i = 1$. This suggests that receivers tend to underestimate the effect of the presence of a second receiver.

3.6.2 Explaining the evidence: level-k vs. Nash

Crawford (2003), Cai and Wang (2006), and Wang et al. (2010) find level-k models to successfully explain subjects' behavior in cheap talk experiments. Following them, in this section we present a test of the level-k model in our setting.

We consider the level-k model that is anchored at L_0 behavior of senders being truth-telling.[43] Thus, L_0 senders have the lowest level of sophistication in the model and simply tell the truth in all cases. L_0 receivers best respond to L_0 senders by always believing their

[42] As it was mentioned before, the difference between receiver 1 and 2 is not due to the identity of the players (all agents are randomly and anonymously assigned to all the possible roles in the game), but due to the fact that the receivers' games are not symmetric.

[43] This is the standard level-k model adopted in most of the literature on cheap talk.

Table 3.15: Behavioral predictions of the level-k model for 3-person games

	Games 12, 23 & 56			Games 13 & 34		
	Sender	Receiver 1	Receiver 2	Sender	Receiver 1	Receiver 2
$L0$	Truth	Trust	Trust	Truth	Trust	Trust
$L1$	Truth	Trust	Trust	Lie	Deny	Deny
$L2$	Truth	Trust	Trust	Truth	Trust	Trust
$L3$	Truth	Trust	Trust	Lie	Deny	Deny
$L4$	Truth	Trust	Trust	Truth	Trust	Trust
...	...	...	...	...	...	...
$L\infty$	Truth	Trust	Trust	...	...	...
NE	Truth	Trust	Trust	Mix	Mix	Mix

opponent. Higher in the hierarchy are level L_1 senders whose actions are the best response to the strategy of L_0 receivers, and level L_1 receivers best respond to level L_1 senders, and so on. Level L_∞ is the limit as $k \to \infty$, if it exists. It is important to note that the limit may not exist, so the predicted strategy for types with high level of k may not coincide with the Nash equilibrium. In our model this will allow us to distinguish level-k predictions from the Nash equilibrium. We follow this procedure for every 2-person and every 3-person game and summarize the theoretical predictions of the level-k model in Tables 3.14 and 3.15. In these two table, sender's strategy is "Truth" if $telling\_truth = 1$, "Lie" if $telling\_truth = 0$, "Tails" if the senders sends message "Tails" regardless of the state, "Heads" if the message is always "Heads", and "Mix" if the sender is playing the mixed strategy. Similar for the responders, "Trust" corresponds to $believing\_sender = 1$, "Deny" corresponds to $believing\_sender = 0$, and "Mix" is the mixed strategy. Whenever the agent is indifferent we assume that he or she uses a mixed strategy.

The behavioral predictions of level-k model for games of no conflict are identical to the Nash equilibrium predictions: "Truth" for the sender; and "Trust" for the receiver. As it can be seen from Tables 3.9 and 3.12, these predictions are well supported by the data both in 2-player and in 3-player games. The games of conflict are more interesting because the Nash equilibrium does not fully explain the data; and (even more importantly) because the standard level-k model differs from the predictions of the Nash equilibrium and so the two hypothesis on agents' behavior can be identified.

Consider 2-player games first. Table 3.16 shows that we can classify senders in three categories:[44] those who always tell the truth; those who always lie; and those who use a mix between lying and telling the truth. A similar observation is true for receivers as well, who can also be classified in those who always believe, those who always distrust, and those who mix. In both cases, the presence of a sizable fraction of agents who behave as L_0 is in conflict with the Nash prediction and suggest that the level-k models may help explaining the evidence. Indeed, the behavior in games 5 and 6 cay be rationalized quite well by the level-k model. Level-0 players may explain why we have agents who always tell the truth or always believe. Agents with a level higher than L_1, on the other hand, find it optimal to mix. So we can explain almost all the data by assuming that agents are between level L_0 and L_2 (or higher). In these games the Nash equilibrium would not be able to explain the behavior of the L_0 players.

The most interesting case, however, is given by games 3 and 4. In these games, level-k model predicts that level L_k senders find it optimal to tell the truth for k even; level L_{k+1} senders find it optimal to lie for $k+1$ odd. Similarly, level L_k receivers believe their partner and level L_{k+1} distrust (see Table 3.14). This implies that as $k \to \infty$ the strategies never converge to the mixing strategy, which is the Nash Equilibrium prediction. This feature allows us to test level-k model against the Nash equilibrium in a sharp way. Table 3.16 clearly shows that neither level-k alone, nor Nash equilibrium alone can fully explain the data in games 3 and 4. The presence of a large set of agents who always believe or always tell the truth (depending on the role), suggests that the predictions of the Nash equilibrium can be improved by assuming a significant share of "naive" agents who behave as level L_0 players. The share of players who mix, on the other hand, is always very substantial (56.5% of receivers and 51.4% of senders). These levels of individual mixing cannot be rationalized

[44] We use $100-81\%$, $80-21\%$, and $20-0\%$ percentage intervals for classification. We have verified that the results are robust to using other classifications: for example, the cutoffs $70\% - 30\%$, and $60\% - 40\%$ (the latter are the cutoffs adopted by Cai and Wang (2006)). A more sophisticated approach is used by Costa-Gomes and Crawford (2006), who classify the agents' strategies by maximum likelihood. Though this approach may lead to more accurate estimates in games with more complex strategy spaces, we feel that our approach is completely adequate in the case with only two actions.

by the standard level-k model *for any level* of k.[45] This evidence, therefore, suggests a significant number of Nash equilibrium players in the pool.

Behavior in the 3-person games leads to similar conclusions. In the games of conflict 13 and 34 the level-k predictions are the same as in games 3 and 4: Level L_k^{**} senders (receivers) find it optimal to tell the truth (believe) for k^{**} even ; level L_k^{*} senders (receivers) find it optimal to lie (not to trust) for k^{*} odd.

From Table 3.12 we observe that most subjects tell the truth in the games of no conflict and mix in the game of conflict. This fact is in contrast with the level-k model, since level-k players never mix, for any k. A sizable fraction of players behave as L_0 by believing the sender when they are receivers, and telling the truth when senders both in games of conflict and no conflict: this is consistent with the presence of "naive" players. The fact that there are few senders that consistently lie and few receivers that consistently deny, however, is also evidence against the level-k model since it would imply that there are no L_k agents for any even k, which seems quite unlikely.

Finally, in order to explore whether the same subjects exhibit lower levels of sophistication in the role of a sender and in the role of a receiver, we classify individual behavior on the basis of their behavior *both* as senders and as receivers. The rationale for this is that if an agent behaves as, say, a L_0 as a sender, perhaps he or she should be expected to behave as a L_0 as a receiver as well. In Table 3.18, we present the distribution of types for the games of conflict. The largest number of subjects behave according to the Nash Equilibrium prediction, the "Mix" strategy: so they mix both as senders and as receivers in games of conflict.[46] In the case of 3-person games, the deviations are much more pronounced and provide a stronger support for level-k model. We note that there is a significant fraction of individuals (9.7% in 2-person games and 13.9% in 3-person games) who tell truth as senders and trust in the receiver's role. However, there are also many individuals who are classified

[45] Of course one can design a more sophisticated type of level-k model (where for example level k players believe that other players types are distributed between 0 and k 1 according to some distribution, as in Camerer et al. (2004)). In our model, however, this more sophisticated level-k solution would help only if we impose strong restrictions on the beliefs of the players that would make them quite indistinguishable from the beliefs of the players in a Nash equilibrium.

[46] Note that some dispersion in the classification of strategies is expected given that agents are using a mixed strategy.

Table 3.16: Two person games - individual strategy profiles

telling_truth

	Truth	Mix	Lie
Games 3&4	41.4%	51.4%	7.1%
Games 5&6	24.3%	61.4%	14.3%

believing_sender

	Trust	Mix	Deny
Games 3&4	24.6%	56.5%	18.8%
Games 5&6	69.0%	28.2%	2.8%

Table 3.17: Three person games - individual strategy profiles

telling_truth

	Truth	Mix	Lie
Game 13	66.7%	14.0%	19.3%
Game 34	55.2%	17.2%	27.6%

believing_sender1

	Trust	Mix	Deny
Game 13	69.1%	20.0%	10.9%
Game 34	49.2%	22.0%	28.8%

believing_sender2

	Trust	Mix	Deny
Game 13	63.0%	16.7%	20.4%
Game 34	50.8%	18.6%	30.5%

Table 3.18: Individual strategy profiles in games of conflict

2-person games

Sender	Truth			Mix			Lie		
Receiver	Trust	Mix	Deny	Trust	Mix	Deny	Trust	Mix	Deny
	9.7%	9.7%	0.0%	22.2%	**51.4%**	1.4%	0.0%	5.6%	0.0%

% out of the total of 72 subjects

3-person games

Sender	Truth			Mix			Lie		
Receiver	Trust	Mix	Deny	Trust	Mix	Deny	Trust	Mix	Deny
	13.9%	23.6%	1.4%	15.3%	**30.6%**	2.8%	5.6%	6.9%	0.0%

% out of the total of 72 subjects

as truth-tellers when senders, but mix in the role of the receivers and vice versa. Therefore, we do not find that only level L_0 senders act L_0 receivers or that only L_0 receivers act as L_0 senders.

In summary, both the games with 2 players and with 3 players seems to suggests that neither the standard level-k model, nor the Nash equilibrium alone can explain the data. Instead a model that assumes a Nash equilibrium that is augmented by a sizable fraction of "naive" agents (L_0 types, who always report truthfully the state or believe the sender) seems to be able to explain the evidence.

3.6.3 Learning

Another explanation for subjects' deviations from the equilibrium predictions could simply be the lack of experience. In this section we explore potential learning effects to see if the behavior of the participants becomes more strategic over time.

If it is true that subjects find that 3-person games are harder to play because of their complexity, then we should observe that learning is more pronounced in the 3-person games than in the 2-person games. Furthermore, we should expect to observe more learning for the receivers in games that are cognitively more complicated for them, that is in games with $cog_i = 1$ for receiver i. For the senders, we will control for both cog_1 and cog_2 to see

Table 3.19: Learning regressions

	2-person games		3-person games		all games	
	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable	Mistake of Sender	Mistake of Receiver	Mistake of Sender	Mistake of Receiver	Mistake of Sender	Mistake of Receiver
Conflict	0.476***	0.481***	0.463***	0.448***	0.469***	0.462***
	(0.00936)	(0.00769)	(0.0139)	(0.0115)	(0.00762)	(0.00751)
Period	0.00217	-0.000968	-0.00159	-0.00256***	-0.000734	-0.00162**
	(0.00456)	(0.00378)	(0.00118)	(0.000978)	(0.000671)	(0.000654)
Conflict experience	-0.00556	0.00257				
	(0.00701)	(0.00576)				
Sender experience	0.00258	-0.00175				
	(0.00237)	(0.00199)				
3-person game					0.00614	0.0177**
					(0.00761)	(0.00764)
Constant	0.0226**	0.0211***	0.0544***	0.0800***	0.0369***	0.0467***
	(0.00986)	(0.00810)	(0.0149)	(0.0124)	(0.00881)	(0.00933)
Observations	648	648	480	960	1,128	1,608
R-squared	0.847	0.895	0.700	0.613	0.787	0.716

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3.20: Learning regressions for 3-person games

	(1)			(2)			(3)			(4)		
Dependent Variable	Mistake of Sender	Mistake of Receiver 1	Mistake of Receiver 2	Mistake of Sender	Mistake of Receiver 1	Mistake of Receiver 2	Mistake of Sender	Mistake of Receiver 1	Mistake of Receiver 2	Mistake of Sender	Mistake of Receiver 1	Mistake of Receiver 2
Conflict	0.508***	0.473***	0.479***	0.507***	0.474***	0.480***	0.506***	0.472***	0.479***	0.506***	0.442***	0.497***
	(0.0199)	(0.0113)	(0.0265)	(0.0199)	(0.0113)	(0.0264)	(0.0200)	(0.0112)	(0.0262)	(0.0418)	(0.0241)	(0.0558)
Period				-0.00131	-0.00156	-0.00348**	-1.08e-05	0.000330	0.000643	0	-0.000553	0.00171
				(0.00118)	(0.000951)	(0.00168)	(0.00172)	(0.00122)	(0.00222)	(0.00254)	(0.00137)	(0.00362)
Cog_1	-0.0156	0.0149		-0.0134	0.0169		-0.0125	0.0677***		-0.0125	0.0713***	
	(0.0150)	(0.0113)		(0.0152)	(0.0113)		(0.0302)	(0.0237)		(0.0318)	(0.0239)	
Cog_2	0.0651***		0.0938***	0.0632***		0.0916***	0.0943***		0.189***	0.0945**		0.200***
	(0.0199)		(0.0265)	(0.0200)		(0.0264)	(0.0312)		(0.0433)	(0.0399)		(0.0529)
Cog_1 x Period							0.000131	-0.00470**		0.000136	-0.00497**	
							(0.00250)	(0.00193)		(0.00269)	(0.00194)	
Cog_2 x Period							-0.00316		-0.00945***	-0.00317		-0.0105**
							(0.00247)		(0.00336)	(0.00346)		(0.00441)
Conflict x Period										-2.00e-05	0.00280	-0.00171
										(0.00346)	(0.00198)	(0.00458)
Constant	-0	0.0193**	0.0208	0.0139	0.0346***	0.0578**	0.000115	0.0163	0.0140	-0	0.0251	0.00269
	(0.0150)	(0.00798)	(0.0216)	(0.0196)	(0.0123)	(0.0280)	(0.0237)	(0.0143)	(0.0318)	(0.0309)	(0.0156)	(0.0440)
Observations	480	480	480	480	480	480	480	480	480	480	480	480
R-squared	0.706	0.793	0.490	0.706	0.794	0.494	0.707	0.797	0.502	0.707	0.798	0.503

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

if more learning occurs in cognitively complicated games.

Table 3.19, where the number of mistakes discussed in the previous section are regressed against the period and several control variables, shows that there are no significant learning effects in the 2-person games. In this table, *period* is a control for the period, the variable *conflict experience* is equal to the number of times that an agent has previously played a game of conflict, the variable *experience as a sender* measures the number of times an agent has played as a sender in previous periods. Not only the period variable, but also the other two measures of experience are insignificant. This is not surprising, since there are few mistakes in 2-person games, and subjects appear to play according to the equilibrium predictions.

Therefore we can focus on learning in 3-person games. Let's first consider the behavior of receivers. In the second specification in Table 3.20, in the regression of the "mistakes" variable we control for the period, whether or not the current game is a game of conflict, and for cog_i. We find that the coefficients in front of the variable *period* are negative and in the case of receiver 2 significant, meaning that there are less mistakes over time, i.e. there is evidence of learning effects. Moreover, learning is more pronounced for receiver 2, which is not surprising given that subjects tend to make more mistakes in receiver 2's role compared to receiver 1's role.[47] In the third specification in Table 3.20, we add an interaction effect $cog_i \times period$. This makes *period* not significant (essentially zero), while the coefficient in front of $cog_i \times period$ is negative and significant at the 1% level. This once again demonstrates that learning occurs in 3-person games that are most complicated.

Consider now learning of the sender in 3-person games. We simultaneously control for cog_1 and cog_2 and find (in the second specification in Table 3.20) that senders are more likely to make mistakes in games that are cognitively complicated for receiver 2 and that there is learning. The fact that senders tend to pay more attention to the game with the first receiver is interesting and can possibly contribute to higher number of mistakes by the second receiver. Since the coefficient in front of *period* is not significant, we do not observe a lot of learning. Adding interaction effects $cog_1 \times period$ and $cog_2 \times period$ demonstrates

[47]This, for example, can be seen from Table 3.12 by comparing the fractions of participants in receiver 1's role and in receiver 2's role who behave according to the theory.

that there is more learning for the sender in games with $cog_2 = 1$, but the effect is still not significant. Interestingly, in the fourth specification we find that after controlling for learning in cog_1 and cog_2 games, learning in just games of conflict disappears (the coefficient in front of $conflict \times period$ is not significant). This is because not all games of conflict are complicated. In fact only game 13 is cognitively complicated (and this effect is already accounted for in cog_2), and the other game of conflict, game 34, is fairly straightforward with just a few mistakes in subjects' strategies. Thus, what matters for the amount of mistakes (and therefore for the high degree of learning) is the cognitive complexity of the game rather than the conflicting nature of a game.

The discussion in this section suggests that subjects' strategies in the 3-person game tend to become closer to the theoretical predictions over time. Learning is concentrated in the games that subjects find harder to play: that is the games with $cog_i = 1$ for receiver i and the games with $cog_2 = 1$ for the sender.

3.7 Conclusion

This article presents results from the first experimental study of cheap talk communication between one sender and multiple receivers. We find that despite the fact that subjects find games with multiple receivers cognitively more complicated than games with just one receiver, there is strong evidence that the effect of an additional audience on information transmission is in line with theoretical predictions. Just like the previous studies (with one sender and one receiver) we find that that there is a significant fraction of agents who are truthful as senders and trusting as receivers in conflict games, which is consistent with the behavior of L_0 type of agents in a level-k behavioral model. However, our findings also suggest that a level-k model alone is not able to explain the data. Furthermore, our analysis of learning suggests that mistakes are made mostly in cognitively complicated games and tend to disappear over time.

The first part of our experiment is a regular 2-person cheap talk game with one sender and one receiver. It provides a benchmark for analyzing the games with multiple receivers as well as allows us to connect to previous experimental literature on cheap talk games.

In the second part of the experiment we test the effect that a second audience has on the information transmission between a sender and a receiver. Our results for 2-person games are consistent with previous findings and the addition of another audience in 3-person games changes subjects behavior according to the predictions in Farrell and Gibbons (1989). Furthermore, the design of 3-person games allows us to distinguish the predictions of level-k model from the Nash equilibrium. We find that neither the level-k nor the Nash equilibrium alone is able to explain the data, while a combination of the two seems to be consistent with the evidence. An experimental test of a game with a richer state and strategy spaces would be an interesting direction for further research. Likewise, how the size of the audience (with more than two receivers) would affect the results remains an open question.

Appendix A

Appendix for Chapter 1

A.1 Proof of Proposition 1.1

We derive the functional forms for $\rho_*^2(\sigma^2), \pi_*^2(\sigma^2), \tilde{\rho_*}^2(\sigma^2)$, and $\tilde{\pi_*}^2(\sigma^2)$ from the following FOCs:

$$[\rho_i^2]: \frac{d}{\left(\frac{1}{\sigma^2} + \frac{1}{\sigma^2 + \rho_i^2 + \pi_*^2} + \frac{n-2}{\sigma^2 + \rho_*^2 + \pi_*^2}\right)^2}(\sigma^2 + \rho_i^2 + \pi_*^2)^{-2} = \frac{K_\rho}{\rho_i^4}$$

$$[\pi_i^2]: \left(\frac{1}{\sigma^2} + \frac{n-1}{\sigma^2 + \rho_*^2 + \pi_i^2}\right)^{-2}(\sigma^2 + \rho_*^2 + \pi_i^2)^{-2} = \frac{K_\pi}{\pi_i^4}$$

in the case of pairwise communication and the following FOCs:

$$[\tilde{\rho_i}^2]: \frac{d(n-1)}{\left(\frac{1}{\sigma^2} + \frac{1}{\sigma^2 + \tilde{\rho_i}^2 + \tilde{\pi_*}^2} + \frac{n-2}{\sigma^2 + \tilde{\rho_*}^2 + \tilde{\pi_*}^2}\right)^2}(\sigma^2 + \tilde{\rho_i}^2 + \tilde{\pi_*}^2)^{-2} = \frac{K_\rho}{\tilde{\rho_i}^4}$$

$$[\tilde{\pi_i}^2]: \left(\frac{1}{\sigma^2} + \frac{n-1}{\sigma^2 + \tilde{\rho_*}^2 + \tilde{\pi_i}^2}\right)^{-2}(\sigma^2 + \tilde{\rho_*}^2 + \tilde{\pi_i}^2)^{-2} = \frac{K_\pi}{\tilde{\pi_i}^4}$$

in the case of a meeting. Imposing the symmetry and noting that $\pi_*^2 = \sqrt{d\frac{K_pi}{K_\rho}}\rho_*^2$ and $\tilde{\pi}_*^2 = \sqrt{d(n-1)\frac{K_\pi}{K_\rho}}\tilde{\rho}_*^2$, we obtain the following quadratic equation for ρ_*^2:

$$\frac{d}{K_\rho}{\rho_*}^4 = \left(\frac{1}{\sigma^2} + \frac{n-1}{\sigma^2 + {\rho_*}^2\left(1 + \sqrt{d\frac{K_\pi}{K_\rho}}\right)}\right)^2 \left(\sigma^2 + {\rho_*}^2\left(1 + \sqrt{d\frac{K_\pi}{K_\rho}}\right)\right)^2$$

and for $\tilde{\rho}_*^2$:

$$\frac{d(n-1)}{K_\rho}\tilde{\rho_*}^4 =$$

$$\left(\frac{1}{\sigma^2} + \frac{n-1}{\sigma^2 + \tilde{\rho_*}^2\left(1+\sqrt{d(n-1)\frac{K_\pi}{K_\rho}}\right)}\right)^2 \left(\sigma^2 + \tilde{\rho_*}^2\left(1+\sqrt{d(n-1)\frac{K_\pi}{K_\rho}}\right)\right)^2,$$

which simplify to be

$$\left(d\sigma^2 - K_\rho\left(1+\sqrt{d\frac{K_\pi}{K_\rho}}\right)^2\right)\rho_*^4 = 2nK_\rho\sigma^2\left(1+\sqrt{d\frac{K_\pi}{K_\rho}}\right)\rho_*^2 + n^2K_\rho\sigma^4$$

$$\left(d(n-1)\sigma^2 - K_\rho\left(1+\sqrt{d(n-1)\frac{K_\pi}{K_\rho}}\right)^2\right)\rho_*^4 =$$
$$2nK_\rho\sigma^2\left(1+\sqrt{d(n-1)\frac{K_\pi}{K_\rho}}\right)\rho_*^2 + n^2K_\rho\sigma^4.$$

Since the coefficients in front of ρ_*^2, $\tilde{\rho}_*^2$, and the free standing coefficients are negative, these equations have positive roots as long as the coefficients in front of ρ_*^4 and $\tilde{\rho}_*^4$ are positive, i.e.:

$$d\sigma^4 > K_\rho\left(1+\sqrt{d\frac{K_\pi}{K_\rho}}\right)^2 \tag{A.1}$$

and

$$d(n-1)\sigma^4 > K_\rho\left(1+\sqrt{d(n-1)\frac{K_\pi}{K_\rho}}\right)^2, \tag{A.2}$$

and such roots are unique and found to be

$$\rho_*^2 = \frac{K_\rho n\sigma^2}{\sqrt{dK_\rho}\sigma^2 - K_\rho\left(1+\sqrt{d\frac{K_\pi}{K_\rho}}\right)}$$
$$\tilde{\rho_*}^2 = \frac{K_\rho n\sigma^2}{\sqrt{d(n-1)K_\rho}\sigma^2 - K_\rho\left(1+\sqrt{d(n-1)\frac{K_\pi}{K_\rho}}\right)}.$$

Substituting the expressions for ρ_*^2 and $\tilde{\rho_*}^2$, we find that

$$\pi_*^2 = \sqrt{d\frac{K_\pi}{K_\rho}} \frac{K_\rho n\sigma^2}{\sqrt{dK_\rho}\sigma^2 - K_\rho\left(1+\sqrt{d\frac{K_\pi}{K_\rho}}\right)}$$

$$\tilde{\pi_*}^2 = \sqrt{d(n-1)\frac{K_\pi}{K_\rho}} \frac{K_\rho n\sigma^2}{\sqrt{d(n-1)K_\rho}\sigma^2 - K_\rho\left(1+\sqrt{d(n-1)\frac{K_\pi}{K_\rho}}\right)}.$$

□

A.2 Proof of Proposition 1.2

Consider the difference between communication precisions.

$$\rho^2 - \tilde{\rho}^2 = n(\chi(1) - \chi(n-1)),$$

and recall that

$$\chi(m) = \frac{K_\rho\sigma^2}{\sqrt{dmK_\rho}\sigma^2 - K_\rho\left(1+\sqrt{dm\frac{K_\pi}{K_\rho}}\right)},$$

therefore

$$\chi'(m) = \frac{-K_\rho\sigma^2\sqrt{dK_\rho}(\sigma^2 - \sqrt{K_\pi})}{\left(\sqrt{dmK_\rho}\sigma^2 - K_\rho\left(1+\sqrt{dm\frac{K_\pi}{K_\rho}}\right)\right)^2}.$$

Therefore $\frac{d\chi(m)}{dm}$ has the opposite sign from $(\sigma^2 - \sqrt{K_\pi})$, and the latter is positive whenever the equilibrium entails a positive amount of communication (See condition (A.1) in the proof of Proposition 1.4)[48] . Thus, $\chi(1) - \chi(n-1) > 0$, and $\rho^2 - \tilde{\rho}^2 > 0$. Similarly,

$$\pi^2 - \tilde{\pi}^2 = \sqrt{d\frac{K_\pi}{K_\rho}}n\chi(1) - \sqrt{d(n-1)\frac{K_\pi}{K_\rho}}n\chi(n-1) > \sqrt{d\frac{K_\pi}{K_\rho}}n(\chi(1) - \chi(n-1)) > 0.$$

□

A.3 Proof of Proposition 1.4

Suppose that $\{\sigma_*^2, \rho_*^2, \pi_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2\}$ is the symmetric equilibrium and consider a deviation by player i (choosing σ_i instead of σ_*^2) at the investment stage. This will result in different communication strategies $\rho_i^2, \pi_i^2, \tilde{\rho_i}^2, \tilde{\pi_i}^2$ which are found from the following optimizations:

$$-u_i = \frac{1}{\frac{1}{\sigma_i^2} + \frac{n-1}{\sigma_*^2+\rho_*^2+\pi_i^2}} + \frac{d(n-1)}{\frac{1}{\sigma_*^2} + \frac{1}{\sigma_i^2+\rho_i^2+\pi_*^2} + \frac{n-2}{\sigma_*^2+\rho_*^2+\pi_*^2}} + K_\rho\frac{n-1}{\rho_i^2} + K_\pi\frac{n-1}{\pi_i^2} + \frac{K}{\sigma_i^2},$$

[48]Note that condition (A.1) implies that $\sqrt{d}\sigma^2 > \sqrt{K_\rho} + \sqrt{dK_\pi} \Rightarrow \sigma^2 > \sqrt{K_\pi}$.

FOC:

$$[\rho_i^2]: \frac{d}{\left(\frac{1}{\sigma_*^2}+\frac{1}{\sigma_i^2+\rho_i^2+\pi_*^2}+\frac{n-2}{\sigma_*^2+\rho_*^2+\pi_*^2}\right)^2}(\sigma_i^2+\rho_i^2+\pi_*^2)^{-2}=\frac{K_\rho}{\rho_i^4}$$

$$[\pi_i^2]: \left(\frac{1}{\sigma_i^2}+\frac{n-1}{\sigma_*^2+\rho_*^2+\pi_i^2}\right)^{-2}(\sigma_*^2+\rho_*^2+\pi_i^2)^{-2}=\frac{K_\pi}{\pi_i^4}$$

And for the meeting:

$$-\tilde{u}_i=$$

$$\frac{1}{\frac{1}{\tilde{\sigma_i}^2}+\frac{n-1}{\sigma_*^2+\tilde{\rho_*}^2+\tilde{\pi_i}^2}}+\frac{d(n-1)}{\frac{1}{\sigma_*^2}+\frac{1}{\tilde{\sigma_i}^2+\tilde{\rho_i}^2+\tilde{\pi_*}^2}+\frac{n-2}{\sigma_*^2+\tilde{\rho_*}^2+\tilde{\pi_*}^2}}+K_\rho\frac{1}{\tilde{\rho_i}^2}+K_\pi\frac{n-1}{\tilde{\pi_i}^2}+F\frac{K}{\sigma_i^2},$$

FOC:

$$[\tilde{\rho_i}^2]: \frac{d(n-1)}{\left(\frac{1}{\sigma_*^2}+\frac{1}{\sigma_i^2+\tilde{\rho_i}^2+\tilde{\pi_*}^2}+\frac{n-2}{\sigma_*^2+\tilde{\rho_*}^2+\tilde{\pi_*}^2}\right)^2}(\tilde{\sigma_i}^2+\tilde{\rho_i}^2+\tilde{\pi_*}^2)^{-2}=\frac{K_\rho}{\tilde{\rho_i}^4}$$

$$[\tilde{\pi_i}^2]: \left(\frac{1}{\tilde{\sigma_i}^2}+\frac{n-1}{\sigma_*^2+\tilde{\rho_*}^2+\tilde{\pi_i}^2}\right)^{-2}(\sigma_*^2+\tilde{\rho_*}^2+\tilde{\pi_i}^2)^{-2}=\frac{K_\pi}{\tilde{\pi_i}^4}$$

Substitute $\{\rho_i^2,\pi_i^2,\tilde{\rho_i}^2,\tilde{\pi_i}^2\}$ found from the FOCs above into u_i and $\tilde{u}_i$ and differentiate with respect to σ_i^2 to obtain optimal investment in information acquisition. Expand $\frac{du}{d\sigma_i^2}=\frac{\partial u}{\partial\sigma_i^2}+\frac{\partial u}{\partial\pi_i^2}\frac{d\pi_i^2}{d\sigma_i^2}+\frac{\partial u}{\partial\rho_i^2}\frac{d\rho_i^2}{d\sigma_i^2}$ and use the Envelope Theorem to conclude that $\frac{du}{d\sigma_i^2}=\frac{\partial u}{\partial\sigma_i^2}$. First, for one-on-one communication:

$$[\sigma_i{}^2]: \left(\frac{1}{\sigma_i^2}+\frac{n-1}{\sigma_*^2+\rho_*^2+\pi_i^2}\right)^{-2}\frac{1}{\sigma_i^4}+\frac{d(n-1)(\sigma_i^2+\rho_i^2+\pi_*^2)^{-2}}{\left(\frac{1}{\sigma_*^2}+\frac{1}{\sigma_i^2+\rho_i^2+\pi_*^2}+\frac{n-2}{\sigma_*^2+\rho_*^2+\pi_*^2}\right)^2}=\frac{K}{\sigma_i^4}$$

Using FOC from ρ_i^2 and π_i^2 optimization, this simplifies to:

$$\frac{(\sigma_*^2+\rho_*^2+\pi_i^2)^2K_\pi}{\pi_i^4\sigma_i^4}+\frac{(n-1)K_\rho}{\rho_i^4}=\frac{K}{\sigma_i^4}.$$

Imposing symmetry, we get:

$$\frac{(\sigma^2+\rho_*^2+\pi_*^2)^2K_\pi}{\pi_*^4\sigma^4}+\frac{(n-1)K_\rho}{\rho_*^4}=\frac{K}{\sigma^4}.$$

Second, for the meeting:

$$[\tilde{\sigma_i}^2]: \left(\frac{1}{\tilde{\sigma_i}^2}+\frac{n-1}{\sigma_*^2+\tilde{\rho_*}^2+\tilde{\pi_*}^2}\right)^{-2}\frac{1}{\tilde{\sigma_i}^4}+\frac{d(n-1)(\tilde{\sigma_i}^2+\tilde{\rho_i}^2+\tilde{\pi_*}^2)^{-2}}{\left(\frac{1}{\sigma_*^2}+\frac{1}{\tilde{\sigma_i}^2+\tilde{\rho_i}^2+\tilde{\pi_*}^2}+\frac{n-2}{\sigma_*^2+\tilde{\rho_*}^2+\tilde{\pi_*}^2}\right)^2}=\frac{K}{\sigma_i^4}$$

Using FOC from $\tilde{\rho_i}^2$ and $\tilde{\pi_i}^2$ optimization, this simplifies to:

$$\frac{K_\pi(\sigma_*^2 + \tilde{\rho_*}^2 + \tilde{\pi_i}^2)^2}{\tilde{\pi_i}^4 \tilde{\sigma_i}^4} + \frac{K_\rho}{\tilde{\rho_i}^4} = \frac{K}{\tilde{\sigma_i}^4}.$$

Imposing symmetry, we get:

$$\frac{K_\pi(\tilde{\sigma}^2 + \tilde{\rho_*}^2 + \tilde{\pi_*}^2)^2}{\tilde{\pi_*}^4 \tilde{\sigma}^4} + \frac{K_\rho}{\tilde{\rho_*}^4} = \frac{K}{\tilde{\sigma}^4}.$$

Finally, if employees do not know whether they will be communicating in a meeting or in pairs, they choose the optimal investment by solving:

$$(1-\alpha)\left(\frac{(\sigma^2(\alpha) + \rho_*^2 + \pi_*^2)^2 K_\pi}{\pi_*^4 \sigma^4(\alpha)} + \frac{(n-1)K_\rho}{\rho_*^4}\right) + \alpha\left(\frac{K_\pi(\sigma^2(\alpha) + \tilde{\rho_*}^2 + \tilde{\pi_*}^2)^2}{\tilde{\pi_*}^4 \sigma^4(\alpha)} + \frac{K_\rho}{\tilde{\rho_*}^4}\right) = \frac{K}{\sigma^4(\alpha)},$$

where α is the anticipated probability of meeting. And the symmetric PBE is defined by the following system of equations:

$$\begin{cases}
\dfrac{d}{\left(\dfrac{1}{\sigma_*^2} + \dfrac{n-1}{\sigma_*^2 + \rho_*^2 + \pi_*^2}\right)^2}(\sigma_*^2 + \rho_*^2 + \pi_*^2)^{-2} = \dfrac{K_\rho}{\rho_*^4} \\
\left(\dfrac{1}{\sigma_*^2} + \dfrac{n-1}{\sigma_*^2 + \rho_*^2 + \pi_*^2}\right)^{-2}(\sigma_*^2 + \rho_*^2 + \pi_*^2)^{-2} = \dfrac{K_\pi}{\pi_*^4} \\
\dfrac{d(n-1)}{\left(\dfrac{1}{\sigma_*^2} + \dfrac{n-1}{\sigma_*^2 + \tilde{\rho_*}^2 + \tilde{\pi_*}^2}\right)^2}(\tilde{\sigma_*}^2 + \tilde{\rho_*}^2 + \tilde{\pi_*}^2)^{-2} = \dfrac{K_\rho}{\tilde{\rho_*}^4} \\
\left(\dfrac{1}{\tilde{\sigma_*}^2} + \dfrac{n-1}{\sigma_*^2 + \tilde{\rho_*}^2 + \tilde{\pi_*}^2}\right)^{-2}(\sigma_*^2 + \tilde{\rho_*}^2 + \tilde{\pi_*}^2)^{-2} = \dfrac{K_\pi}{\tilde{\pi_*}^4} \\
(1-\alpha)\left(\dfrac{(\sigma^2 + \rho_*^2 + \pi_*^2)^2 K_\pi}{\pi_*^4 \sigma^4} + \dfrac{(n-1)K_\rho}{\rho_*^4}\right) + \alpha\left(\dfrac{K_\pi(\sigma^2 + \tilde{\rho_*}^2 + \tilde{\pi_*}^2)^2}{\tilde{\pi_*}^4 \sigma^4} + \dfrac{K_\rho}{\tilde{\rho_*}^4}\right) = \dfrac{K}{\sigma^4}
\end{cases}$$

This system has unique solution for positive values $\{\sigma_*^2, \rho_*^2, \pi_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2\}$, and the solution is defined by:

$$\begin{cases}
\sigma_*^2 = \dfrac{-B + \sqrt{B^2 - 4AC}}{2A} \\
\rho_*^2 = \dfrac{K_\rho n \sigma_*^2}{\sqrt{dK_\rho}\sigma_*^2 - K_\rho\left(1 + \sqrt{d\dfrac{K_\pi}{K_\rho}}\right)} \\
\pi_*^2 = \sqrt{d\dfrac{K_\pi}{K_\rho}}\rho_*^2 \\
\tilde{\rho_*}^2 = \dfrac{K_\rho n \sigma_*^2}{\sqrt{d(n-1)K_\rho}\sigma_*^2 - K_\rho\left(1 + \sqrt{d(n-1)\dfrac{K_\pi}{K_\rho}}\right)} \\
\tilde{\pi_*}^2 = \sqrt{d(n-1)\dfrac{K_\pi}{K_\rho}}\tilde{\rho_*}^2,
\end{cases}$$

where

$$
\begin{aligned}
A =& d(1+d(n-1))(n-1) \\
B =& 2(1-d)(n-1)\left(\sqrt{dK_\rho}+d\sqrt{K_\pi}\right)(n-1)-\alpha\left((n-1)\sqrt{dK_\rho}-\sqrt{dK_\rho(n-1)}\right) \\
C =& -(n-1) \\
& \left(-d\left(-Kn^2+K_\pi(n-1)(n-1+d)\right)-K_\rho(n-1+d)\left(1+2\sqrt{\frac{dK_\pi}{K_\rho}}\right)(n-1)\right) \\
& -(n-1)K_\rho(n-1+d)\alpha\left(-2\left(1+\sqrt{\frac{dK_\pi}{K_\rho}}+\sqrt{\frac{dK_\pi(n-1)}{K_\rho}}\right)+n+2\sqrt{\frac{dK_\pi}{K_\rho}}n\right)\Box
\end{aligned}
$$

A.4 Proof of Proposition 1.5

First, show the result for the case when agents expect pairwise communication. Recall from Proposition 1.4 that the equilibrium choice of individual investment in private information is given by:

$$\sigma_*^2=\frac{-B+\sqrt{B^2-4AC}}{2A},$$

where

$$
\begin{aligned}
A &= d(1+d(n-1))(n-1) \\
B &= 2(1-d)(n-1)^2\left(\sqrt{dK_\rho}+d\sqrt{K_\pi}\right) \\
C &= (n-1)\left(d\left(-Kn^2+K_\pi(n-1)(n-1+d)\right)\right) \\
&\quad +(n-1+d)(n-1)^2\left(K_\rho+2\sqrt{dK_\pi K_\rho}\right).
\end{aligned}
$$

To find the socially optimal amount of investment in private information, the planner solves:

$$\min_{\sigma^2}\frac{1+d(n-1)}{\dfrac{1}{\sigma^2}+\dfrac{n-1}{\sigma^2+{\rho_*}^2+{\pi_*}^2}}+K_\rho\frac{n-1}{{\rho_*}^2}+K_\pi\frac{n-1}{{\pi_*}^2}+\frac{K}{\sigma^2},$$

which gives the following FOC that determines $\hat{\sigma}_*^2$:

$$
\begin{aligned}
&\sqrt{dK_\rho K_\pi}(n-1)+d^2(n-1)\hat{\sigma}_*^4 \\
&\qquad +d\left(-\sqrt{dK_\rho K_\pi}+K_\rho(n-1)+K_\pi(n-1)-Kn+\sqrt{dK_\rho K_\pi}n+\hat{\sigma}_*^4\right)=0,
\end{aligned}
$$

and the unique positive solution is

$$\hat{\sigma}_*^2=\frac{\sqrt{(1-n)(dK_\rho+dK_\pi+\sqrt{dK_\rho K_\pi}+d\sqrt{dK_\rho K_\pi})+dKn}}{\sqrt{d-d^2+d^2n}}.$$

Let $D=d(1+d(n-1))(\sigma_*^2-\hat{\sigma}_*^2)$, then Taylor expansion for D as $n\to\infty$ gives:

$$D\approx d\sqrt{dK-K_\rho-dK_\pi-2\sqrt{dK_\rho K_\pi}}n\sqrt{n}>0,$$

and thus $\sigma_*^2 > \hat{\sigma}_*^2$ for large enough n.

Similarly, show the result for the case when agents expect a meeting. Recall from Propostion 1.4 that the equilibrium choice of individual investment in private information is given by:

$$\tilde{\sigma}_*^2 = \frac{-\tilde{B} + \sqrt{\tilde{B}^2 - 4\tilde{A}\tilde{C}}}{2\tilde{A}},$$

$$\begin{aligned}
\tilde{A} &= d(1 + d(n-1))(n-1) \\
\tilde{B} &= 2(1-d)(n-1)\left(d\sqrt{K_\pi}(n-1) + \sqrt{dK_\pi(n-1)}\right) \\
\tilde{C} &= (n-1)\left(-dKn^2 + (n-1+d)(n-1)\left(K_\rho + 2\sqrt{dK_\pi K_\rho} + dK_\pi\right)\right) \\
&\quad - (n-1)(n-1+d)\left(-2\text{ka} - 2\sqrt{dK_\pi K_\rho(n-1)} + nK_\rho + 2\sqrt{dK_\pi K_\rho}(n-1)\right).
\end{aligned}$$

The planner's maximization problem is

$$\min_{\tilde{\sigma}^2} \frac{1 + d(n-1)}{\dfrac{1}{\tilde{\sigma}^2} + \dfrac{n-1}{\tilde{\sigma}^2 + \tilde{\rho}_*{}^2 + \tilde{\pi}_*^2}} + K_\rho \frac{1}{\tilde{\rho}_*^2} + K_\pi \frac{n-1}{\tilde{\pi}_*^2} + \frac{K}{\tilde{\sigma}^2},$$

which gives the following FOC that determines $\hat{\tilde{\sigma}}_*^2$:

$$K_\rho + K_\pi(n-1) + \sqrt{\frac{K_\rho K_\pi(n-1)}{d}} + \sqrt{dK_\rho K_\pi(n-1)} - Kn + \hat{\tilde{\sigma}}_*^4 + d(n-1)\hat{\tilde{\sigma}}_*^4 = 0,$$

and the unique positive solution is

$$\hat{\tilde{\sigma}}_*^2 = \frac{\sqrt{-K_\rho + K_\pi - \sqrt{\frac{K_\rho K_\pi(n-1)}{d}} - \sqrt{dK_\rho K_\pi(n-1)} + Kn - K_\pi n}}{\sqrt{1 - d + dn}}.$$

Let $\tilde{D} = d(1 + d(n-1))(\tilde{\sigma}_*^2 - \hat{\tilde{\sigma}}_*^2)$, then Taylor expansion for $\tilde{D}$ as $n \to \infty$ gives:

$$\tilde{D} \approx d^2 \frac{\sqrt{K - K_\pi}}{\sqrt{d}} n\sqrt{n} > 0,$$

and thus $\tilde{\sigma}_*^2 > \hat{\tilde{\sigma}}_*^2$ for large enough n. To demonstrate that the condition for n having to be large enough is indeed necessary, we give the following example.

Small n

- *Pairwise communication.* Let $n = 3$, $K_\rho = 0.3$, $K_\pi = 0.05$, $d = 0.3$, and $K = 0.9$. Then, $\sigma_*^2 = 0.309313 < 0.941615 = \hat{\sigma}_*^2$.

- *Meeting.* Let $n = 3$, $K_\rho = 3$, $K_\pi = .03$, $d = .01$, $K = 100$. Then, $\tilde{\sigma}_*^2 = 14.0703 < 16.9386 = \hat{\tilde{\sigma}}_*^2$.

□

A.5 Proof of Proposition 1.6

This proposition is a particular case of Proposition 1.8, and therefore follows from it. □

A.6 Proof of Lemma 1.1

$v(\sigma^2) - \tilde{v}(\sigma^2)$ is an increasing function of σ^2, because:

$$v - \tilde{v} = -\sqrt{dK_\rho} + \sqrt{\frac{K_\rho}{d}} - \sqrt{dK_\rho(n-1)} - \frac{\sqrt{dK_\rho}}{dn} - \frac{\sqrt{dK_\rho(n-1)}}{dn} + \sqrt{dK_\rho}n -$$
$$(K_\rho + \sqrt{dK_\rho K_\pi} + \frac{\sqrt{dK_\rho K_\pi}}{d} - \frac{2K_\rho}{n} - \frac{\sqrt{dK_\rho K_\pi}}{n} - \frac{\sqrt{dK_\rho K_\pi}}{dn} -$$
$$\frac{\sqrt{dK_\rho K_\pi(n-1)}}{n} - \frac{\sqrt{dK_\rho K_\pi(n-1)}}{dn})\frac{1}{\sigma^2} = a - b\frac{1}{\sigma^2},$$

for some a, b. To see that a and b are positive, check that if $n = 2$, then $a = b = 0$, and as n increases, a and b increase:

$$\frac{da}{dn} = \sqrt{dK_\rho}\left(-\frac{1}{2\sqrt{n-1}} + \frac{1}{dn^2} - \frac{1}{2dn\sqrt{n-1}} + \frac{\sqrt{n-1}}{dn^2} + 1\right) > 0$$

for $n > 2$, because $\frac{1}{2\sqrt{n-1}} < 1$ and $\frac{1}{2dn\sqrt{n-1}} < \frac{\sqrt{n-1}}{dn^2}$ got $n > 2$. The fact that $\frac{db}{dn} > 0$ is obvious. □

A.7 Proof of Proposition 1.8

Compute $\frac{d\sigma_*^2}{d\alpha}$:

$$\frac{d\sigma_*^2}{d\alpha} = \frac{1}{2A}\left(-\frac{dB}{d\alpha} + \frac{1}{2\sqrt{B^2 - 4AC}}\left(2B\frac{dB}{d\alpha} + 4A\frac{dC}{d\alpha}\right)\right)$$

Clearly, $A > 0$, and

$$-\frac{dB}{d\alpha} = 2(1-d)\sqrt{dK_\rho}\left((n-1) - \sqrt{(n-1)}\right) > 0,$$

since $n \geq 2$. Let $X = \frac{1}{2(1-d)^2}\left(2B\frac{dB}{d\alpha} + 4A\frac{dC}{d\alpha}\right)$, so that it is sufficient to show that $X \geq 0$ for all n:

$$X = \left(\alpha\left(\sqrt{dK_\rho}(n-1) - \sqrt{dK_\rho(n-1)}\right) - \left(\sqrt{dK_\rho} + d\sqrt{K_\pi}\right)(n-1)\right)$$
$$\left(\sqrt{dK_\rho}(n-1) - \sqrt{dK_\rho(n-1)}\right) + dK_\rho(1 + d(n-1))(-1 + d + n)$$
$$\left(-2\left(1 + \sqrt{\frac{dK_\pi}{K_\rho}} + \sqrt{\frac{dK_\pi(n-1)}{K_\rho}}\right) + n + 2\sqrt{\frac{dK_\pi}{K_\rho}n}\right).$$

Then, $X = 0$ for $n = 2$. Consider the derivative of X with respect to n:

$$\frac{dX}{dn} = \sqrt{dK_\rho K_\pi}X_1 + X_2,$$

where

$$X_1 = 2d\left(n-1+4d-6dn+2d^2(n-1)\right) - d\sqrt{(n-1)}\left(\frac{6d}{n-1}+\frac{3}{2}+3d^2\right) + 10d^2n\sqrt{\frac{1}{n-1}} + d^2n^2\left(6-5\sqrt{\frac{1}{n-1}}\right)$$

and

$$X_2 = d^3K_\rho(2n-3) + d^2K_\rho(6+n(3n-8)) + \frac{1}{2}dK_\rho\left(-2+3\sqrt{n-1}+\alpha\left(-2-6\sqrt{n-1}+4n\right)\right).$$

It is easy to see that $X_2 > 0$ for any $n \geq 2$, because $6+n(3n-8) > 0$ and $-2-6\sqrt{n-1}+4n \geq 0$ for $n \geq 2$. To prove that $X_1 > 0$, note that if $n = 2$, $X_1 = d/2 + 2d^2 + d^3 > 0$, and:

$$\frac{dX_1}{dn} = \frac{1}{4}d\left(8+d^2\left(16-\frac{6}{\sqrt{n-1}}\right)-\frac{3}{\sqrt{n-1}}\right) + \frac{1}{2}d^2\left(-24+\frac{1}{(n-1)^{3/2}}-15\sqrt{n-1}+24n\right) > 0,$$

for any $n \geq 2$.

Thus, we've shown that $2B\dfrac{dB}{d\alpha} + 4A\dfrac{dC}{d\alpha} > 0$ for all $n \geq 2$. □

A.8 Proof of Proposition 1.9

As it was shown in Section 1.3.2, the fixed point equation that determines equilibrium probability of meeting is $\hat{\alpha} = F(c_n(\hat{\alpha}))$, where

$$c_n(\hat{\alpha}) = v(\sigma_*^2(\hat{\alpha})) - \tilde{v}(\sigma_*^2(\hat{\alpha})).$$

We show in Proposition 1.8 that $\sigma_*^2(\hat{\alpha})$ is an increasing function of $\hat{\alpha}$. Moreover, in Lemma 1.1, we demonstrate that $v(\sigma^2) - \tilde{v}(\sigma^2)$ is an increasing function of σ^2. Therefore, $F(c_n(\hat{\alpha}))$ is an increasing function of $\hat{\alpha}$.

In Figure A.1, we graphically represent the increasing function $F(c_n(\hat{\alpha}))$ and possible fixed point solutions. We assume that the support of $F(.)$, $[0, \bar{c}]$ is large enough so that $F(c_n(1)) \leq 1$ and that $F(.)$ is continuous. This guarantees at least one solution to the fixed point equation. Depending on the actual functional form of $F(.)$ this solution might or might not be unique. □

A.9 Proof of Proposition 1.10

Meeting cost is common knowledge

The proof for the case of costs being common knowledge is outlined in the text, two things need to be shown to complete it:

1. $c^1_{nc} > c_c$ and $c^2_{nc} > c_c$

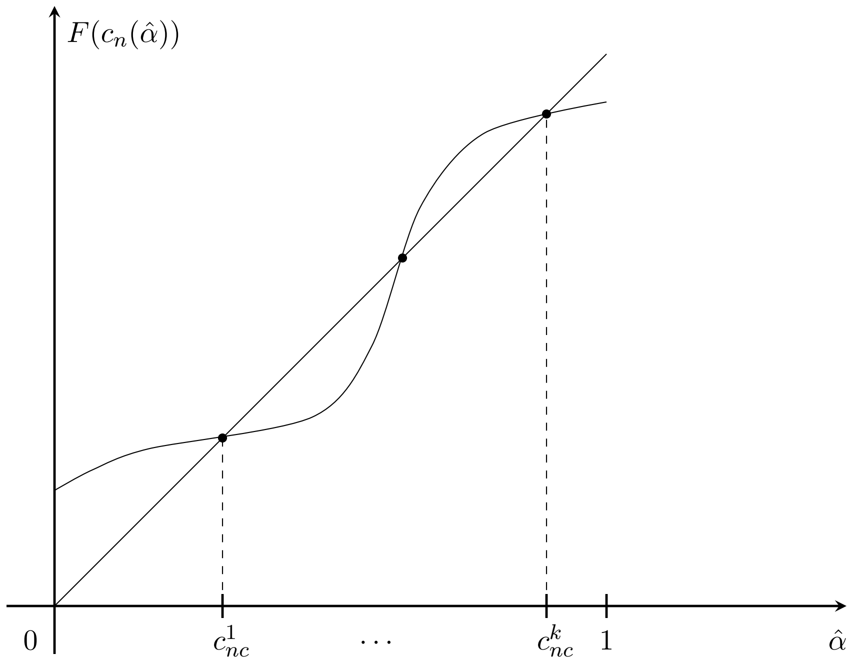

Figure A.1: Equilibrium probability of meeting in the case without commitment and private knowledge of the cost of a meeting

2. $c_{nc}^1 < c_{nc}^2$.

These comparisons follow directly from the second part of the proof of this proposition (when meeting cost is private knowledge of the firm):

Meeting cost is private knowledge of the firm

In Section 1.3 we show that in an equilibrium $\{\sigma_*^2, \tilde{\sigma_*}^2, \rho_*^2, \pi_*^2, \tilde{\rho_*}^2, \tilde{\pi_*}^2\}$, ex-ante probability of meeting is determined by the following fixed point equations:

$$\alpha_c = F(u(\sigma_*^2) - \tilde{u}(\tilde{\sigma_*}^2))$$
$$\alpha_n = F(v(\sigma^2) - \tilde{v}(\sigma^2)),$$

in the case with and without commitment respectively and where $\sigma^2 \in [\sigma_*^2, \tilde{\sigma_*}^2]$ corresponds to any of the possible multiple equilibrium without commitment. Therefore, $\alpha_c < \alpha_n$ if and only if

$$u(\sigma_*^2) - \tilde{u}(\tilde{\sigma_*}^2) < v(\sigma^2) - \tilde{v}(\sigma^2). \tag{A.3}$$

By Lemma 1.1, $v(\sigma^2) - \tilde{v}(\sigma^2)$ is an increasing function of σ^2. Therefore, RHS of equation (A.3) is equal to $a - b\dfrac{1}{\sigma^2}$ and is increasing in σ^2. Thus, to prove the inequality for all $\sigma^2 \in [\sigma_*^2, \tilde{\sigma_*}^2]$, it is enough to show the inequality for $\sigma^2 = \sigma_*^2$:

$$u(\sigma_*^2) - \tilde{u}(\tilde{\sigma_*}^2) < v(\sigma_*^2) - \tilde{v}(\sigma_*^2) \Leftrightarrow$$

$$v(\sigma_*^2) - \tilde{v}(\tilde{\sigma_*}^2) + K\left(\frac{1}{\sigma_*^2} - \frac{1}{\tilde{\sigma_*}^2}\right) < v(\sigma_*^2) - \tilde{v}(\sigma_*^2) \Leftrightarrow$$

$$K\left(\frac{1}{\sigma_*^2}-\frac{1}{\tilde{\sigma_*}^2}\right)<\tilde{v}(\tilde{\sigma_*}^2)-\tilde{v}(\sigma_*^2). \tag{A.4}$$

In equation (A.4), the LHS corresponds to the additional cost agents pay to improve the variance of their private signal from $\tilde{\sigma}_*^2$ to σ_*^2. The RHS is the benefit from better private information that agents get in communicating in a meeting. Therefore, the firm will choose to commit to fewer meetings whenever the cost is less that the benefit. Compute:

$$\begin{aligned}\tilde{v}(\tilde{\sigma_*}^2)-\tilde{v}(\sigma_*^2)=&\frac{\tilde{\sigma_*}^2-\sigma_*{}^2}{dK_\pi n\tilde{\sigma_*}^2\sigma_*{}^2}\\&\left(K_\pi(1+d)\sqrt{dK_\rho K_\pi(n-1)}+dK_\pi(K_\rho+K_\pi(n-1)+(1+d(n-1))\tilde{\sigma_*}^2\sigma_*{}^2)\right).\end{aligned}$$

Since $\tilde{\sigma_*}^2>\sigma_*^2$, the inequality (A.4) simplifies further to

$$K<\frac{K_\pi(1+d)\sqrt{dK_\rho K_\pi(n-1)}+dK_\pi(K_\rho+K_\pi(n-1)+(1+d(n-1))\tilde{\sigma_*}^2\sigma_*{}^2)}{dnK_\pi}. \tag{A.5}$$

Consider the Taylor expansion for $\tilde{\sigma_*}^2$ and σ_*^2 as $n\to\infty$:

$$\begin{aligned}\tilde{\sigma_*}^2&\approx\frac{1}{d}\sqrt{K-K_\pi}\sqrt{n}\\ \sigma_*^2&\approx\frac{1}{d}\sqrt{dK-(\sqrt{K_\rho}+\sqrt{dK_\pi})^2}\sqrt{n}.\end{aligned}$$

Therefore, we can see that the RHS in inequality (A.5) increases as $O(n)$ as n increases and thus must be true for $n>\bar{n}$ for some $\bar{n}$.

Small n

If n is small, inequality (A.5) does not hold for all parameter values. Consider $n=3, K_\rho=0.044, K_\pi=0.108, d=0.131, K=0.992$, then $\sigma_*^2=1.169$, $\tilde{\sigma_*}^2=1.487$ and $RHS=0.919<K$.

With this particular combination of parameters, the firm actually prefers to commit to a larger number of meetings than the number of meetings in the case without commitment. Such a policy allows the firm to save on the cost of information acquisition and improve the precision of communication, which is better when private information is not as good. Formally, we can consider the derivative

$$\frac{d\rho_*^2(\sigma^2)}{d\sigma^2}=\frac{d}{d\sigma^2}\left(\frac{K_\rho n\sigma^2}{\sqrt{dK_\pi}\sigma^2-K_\rho\left(1+\sqrt{d\frac{K_\pi}{K_\rho}}\right)}\right)<0,$$

therefore as σ^2 decreases, ρ_*^2 increases. As n becomes large, the dominant term in the denominator of the expression for ρ_*^2 becomes $\sqrt{dK_\rho}\sigma^2$, since σ^2 increases as $O(\sqrt{n})$, and therefore the undesirable effect of the increase in communication noise vanishes with large n.

$\square$

Appendix B

Appendix for Chapter 2

B.1 Proof of Theorem 2.1

Equation (2.1) does not depend on l^*, thus we proceed by first characterizing equilibrium values for h and then substituting them in equation (2.2) to find the equilibrium values for l. To consider different cases for the parameter values and implied equilibria for h, simplify $\Psi(h)$:

$$\begin{aligned}
\Psi(h) &= \frac{xh(1-dh-c)}{dh+c} = xh\left(\frac{1}{dh+c}-1\right) \\
\Psi'(h) &= x\left(\frac{c}{(c+dh)^2}-1\right) \\
\Psi''(h) &= -\frac{2cdx}{(c+dh)^3} < 0.
\end{aligned}$$

Thus we know that $\Psi'(0) > 0$, since $c < 1$, therefore $\Psi(h)$ is initially increasing. Since $\Psi''(h) < 0$, for all h, $\Psi(h)$ is strictly concave on $[0,1]$. Adding continuity of $\Psi(h)$ (which arises from continuity of $F(\beta)$), we conclude that $\Psi(h)$ can have one of the shapes in Figure B.1. Note that irrespective of the parameter values, $h^* = 0$ is always an equilibrium (can be verified by comparing the payoffs from ND and H strategies).

Case 1. $\Psi'(0) \leq 1 \Leftrightarrow x - xc - c \leq 0$

In this case, $h^* = 0$ is the unique equilibrium value of h. Concavity of $\Psi(h)$ guarantees that that there is no interior equilibrium ($\Psi(h) < h$ for all h). Finally, $h = 1$ is not an equilibrium, because type $t = 1$ under such parameter values prefers the ND strategy:

$$\begin{aligned}
&x - xc - c \leq 0 \Rightarrow x - xc - xd - c - d < 0 \Rightarrow \\
&\frac{x(1-d-c)}{d+c} < 1 \Rightarrow (1+x)(1-d-c) < 1.
\end{aligned}$$

We conclude that in this case there is a unique stable equilibrium $\boxed{h^* = 0}$.

Case 2A. $\Psi'(0) > 1$ and $\Psi(1) \geq 1 \Leftrightarrow d \leq \dfrac{x - cx - c}{1+x} < 1 - c$

In this case, $h^* = 0$ is an unstable equilibrium value for h. Since $\Psi(h)$ is concave and $\Psi(1) \geq 1$, there is no interior equilibrium. However, $h^* = 1$ is the unique stable equilibrium value for h in this case. First check that no one prefers to deviate to the ND strategy:

$$d \leq \frac{x - cx - c}{1+x} \Rightarrow (1+x)(1-d-c) \geq 1,$$

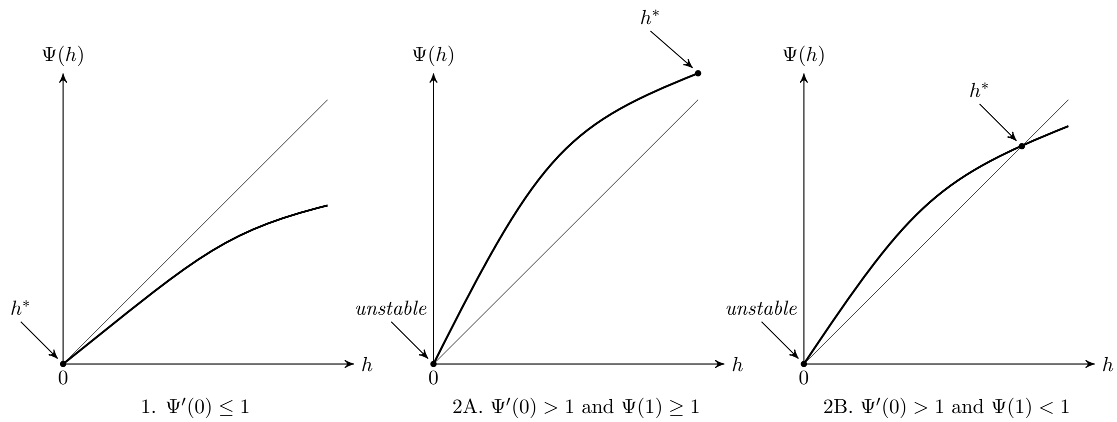

Figure B.1: Equilibrium h^*

and $\Psi(1) > 1$ implies that this equilibrium value for h is stable. Therefore the unique stable equilibrium is $\boxed{h^* = 1}$.

Case 2B. $\Psi'(0) > 1$ and $\Psi(1) < 1 \Leftrightarrow \dfrac{x - cx - c}{1+x} < d < 1 - c$

Again, $h^* = 0$ is an unstable equilibrium value for h in this case. Also, as we have seen in Case 1, $\dfrac{x - cx - c}{1+x} < d$ implies that $h^* = 1$ is not an equilibrium. However, continuity and $\Psi(1) < 1$ mean that there is an interior equilibrium:

$$h^* = xh^* \left(\frac{1}{dh^* + c} - 1 \right) \Leftrightarrow h^* = \frac{x - xc - c}{d(1+x)} < 1,$$

and by concavity of $\Psi(h)$, it is a stable equilibrium value. Thus, in this final case, we find the unique stable equilibrium value to be $\boxed{h^* = \dfrac{x - xc - c}{d(1+x)}}$.

We proceed by characterizing l^* for each stable equilibrium value h^*. Because Equation 2 contains an arbitrary probability function $F(\beta)$, we will not be able to find all equilibria explicitly. Instead, for each set of parameter values we will focus on finding a stable equilibrium value with the lowest l^*, which would correspond to an optimal equilibrium from the firm's point of view. Again, we begin by studying $\Phi(l)$:

$$\begin{aligned}
\Phi(l) &= \int_0^{h^*} \int_0^{\beta_l(t)} f(\beta)\, d\beta\, dt = \int_0^{h^*} F\left(\frac{\alpha l}{\alpha l + (t + xh^*)(dl + c)} \right) dt, \\
\Phi'(l) &= \int_0^{h^*} f(\beta_l(t)) \frac{\partial \beta_l}{\partial l}\, dt \\
&= \int_0^{h^*} f\left(\frac{\alpha l}{\alpha l + (t + xh^*)(dl + c)} \right) \frac{\alpha c(t + xh^*)}{(c(t + xh^*) + l(\alpha + d(t + xh^*)))^2}\, dt > 0,
\end{aligned}$$

$$\begin{aligned}
\Phi'(0) &= \int_0^{h^*} f(0) \frac{\alpha}{c(t + xh^*)}\, dt = \frac{\alpha}{c} f(0) \ln(\frac{x+1}{x})\, dt \text{ if } h^* \neq 0 \text{ and 0 otherwise,} \\
\Phi''(l) &= \int_0^{h^*} f'(\beta_l(t)) \left(\frac{\partial \beta_l}{\partial l} \right)^2 + f(\beta_l(t)) \frac{\partial \beta_l^2}{\partial^2 l}\, dt.
\end{aligned}$$

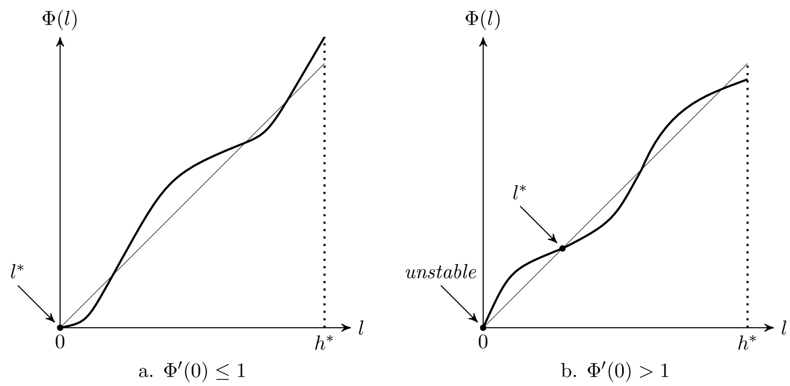

Figure B.2: Equilibrium l^*

Therefore, we know that $\Phi(l)$ is increasing; however, its concavity depends on $F(\beta)$, and thus potentially we might have 0, 1, or more interior equilibria. Figure B.2 demonstrates the possible cases that characterize equilibrium values for l^*.

Case 1. $h^* = 0$

Since $l^* \leq h^*$, $l^* = 0$, and this is a stable equilibrium value for l, therefore $\boxed{h^* = 0,\, l^* = 0}$.

Case 2Aa. $h^* = 1$ and $\Phi'(0) \leq 1 \Leftrightarrow \dfrac{\alpha}{c} f(0) \ln(\dfrac{x+1}{x}) \leq 1$

In this case, $l^* = 0$ is a stable equilibrium value for l. While we can have many other stable and unstable equilibria, this one must be the optimal one from the firm's point of view. Therefore, we get $\boxed{h^* = 1,\, l^* = 0}$.

Case 2Ab. $h^* = 1$ and $\Phi'(0) > 1 \Leftrightarrow \dfrac{\alpha}{c} f(0) \ln(\dfrac{x+1}{x}) > 1$

In this case, $l^* = 0$ is an unstable equilibrium value. Since $F(\beta) \leq 1$ and $F(\beta) < 1$ for $\beta < 1$ ($f(\beta)$ is continuous and non-atomic), we know that $\Phi(1) < 1$. Thus, there must be at least one interior root to Equation 2. Since $\Phi'(0) > 1$, $\Phi(l)$ intersects the diagonal from above and therefore the first (smallest positive) interior root is a stable equilibrium value for l. Therefore, $\boxed{h^* = 1,\, l^* = \Phi(l^*)}$.

Case 2Ba. $h^* = \dfrac{x - xc - c}{d(1+x)}$ and $\Phi'(0) \leq 1 \Leftrightarrow \dfrac{\alpha}{c} f(0) \ln(\dfrac{x+1}{x}) \leq 1$

This case is just like Case 2Aa, therefore $\boxed{h^* = \dfrac{x - xc - c}{d(1+x)},\, l^* = 0}$.

Case 2Bb. $h^* = \dfrac{x - xc - c}{d(1+x)}$ and $\Phi'(0) > 1 \Leftrightarrow \dfrac{\alpha}{c} f(0) \ln(\dfrac{x+1}{x}) > 1$

This case is just like Case 2Ab. The only difference is that we use condition $\Phi(h^*) < h^*$ instead of $\Phi(1) < 1$. Just like in 2Ab, $\Phi(h^*) < h^*$, because $F(\beta) < 1$ for $\beta < 1$. Therefore, $\boxed{h^* = \dfrac{x - xc - c}{d(1+x)},\, l^* = \Phi(l^*)}$. □

B.2 Proof of Theorem 2.2

In order to prove the theorem, we will construct a parameterized family of CDFs, ranked by the degree of present-bias, which includes both distribution $F(\beta)$ and $H(\beta)$. We will use a lemma that shows the result of the theorem for such parametrized family, and the theorem will be a simple corollary to the lemma, showing that the equilibrium number of l-mailers corresponding to the H-distribution is larger than the one corresponding to the F-distribution. Lemma B.1 uses the condition from Theorem 2.1 that $\Phi'(l) < 1$ at a stable interior equilibrium to show that the equilibrium amount of l-mail increases as the distribution of workers becomes more present-biased. Intuitively, a stable equilibrium guarantees that there is a multiplier effect - if some people decide to check l-mail, this induces more people to check l-mail during the day. We find that social forces amplify the present-bias effect of workers and therefore a greater degree of present-bias leads to a larger equilibrium amount of l-mail.

Lemma B.1 *Consider $F(\beta, a)$ - a family of cumulative distribution functions, parametrized by a and differentiable for all values of β, a. Suppose $\frac{\partial F(\beta,a)}{\partial a} > 0$ for all β, meaning that $F(\beta, a)$ becomes more present-biased as a increases. Then, if l_a^* is the optimal stable equilibrium corresponding to $F(\beta, a)$, then $\frac{dl_a^*}{da} > 0$.*

Proof. Differentiating equation (2.2) with respect to a gives:

$$\begin{aligned}\frac{dl}{da} &= \frac{\partial\Phi(l)}{\partial l}\frac{dl}{da} + \frac{\partial\Phi(l)}{\partial a} \Leftrightarrow \\ \frac{dl}{da} &= \left(1 - \frac{\partial\Phi(l)}{\partial l}\right)^{-1}\frac{\partial\Phi(l)}{\partial a}.\end{aligned}$$

Since $\frac{\partial\Phi(l)}{\partial l} < 1$ at the optimal stable equilibrium, the multiplier in front of $\frac{\partial\Phi(l)}{\partial a}$ is positive and is larger than 1. Therefore, it is enough to show that $\frac{\partial\Phi(l)}{\partial a} > 0$:

$$\begin{aligned}\frac{\partial\Phi(l)}{\partial a} &= \frac{\partial}{\partial a}\int_0^{h^*} F(\beta_l(t), a)dt \\ &= \int_0^{h^*}\frac{\partial F(\beta_l(t), a)}{\partial a}dt > 0,\end{aligned}$$

since $\frac{\partial F(\beta,a)}{\partial a} > 0$ for any β, and the lemma holds. ■

Using Lemma B.1, the proof of Theorem 2.2 becomes a simple corollary.

Given $H(\beta)$ and $F(\beta)$, let the family of distributions be the weighted average of $H(\beta)$ and $F(\beta)$:

$$T(\beta, a) = aH(\beta) + (1-a)F(\beta),$$

for $a \in [0, 1]$. Then $F(\beta) = T(\beta, 0)$, $G(\beta) = T(\beta, 1)$, and $\frac{\partial T(\beta,a)}{\partial a} = H(\beta) - F(\beta) > 0$, therefore we can apply the lemma to conclude that $\frac{dl^*}{da} > 0$ and therefore $l_H^* > l_F^*$. □

B.3 Proof of Theorem 2.3

$$\frac{dY}{d\alpha} = -\int_0^{h^*}\frac{dF(\beta_{l^*}(t))}{d\alpha}(t + xh^*)(dl^* + c)\,dt - \int_0^{h^*} d(t + xh^*)F(\beta_{l^*}(t))\frac{dl^*}{d\alpha}\,dt$$

$$\begin{aligned}
\frac{dl^*}{d\alpha} &= \int_0^{h^*} \frac{dF(\beta_{l^*}(t))}{d\alpha}\, dt \\
&= \int_0^{h^*} \frac{\partial F(\beta_{l^*}(t))}{\partial \beta} \frac{d\beta_{l^*}(t)}{d\alpha}\, dt \\
&= \int_0^{h^*} f(\beta_{l^*}(t)) \left[\frac{\partial \beta_{l^*}(t)}{\partial l} \frac{dl^*}{d\alpha} + \frac{\partial \beta_{l^*}(t)}{\partial \alpha} \right] dt.
\end{aligned}$$

Therefore,

$$\frac{dl^*}{d\alpha} = \left(1 - \frac{\partial \Phi(l)}{\partial l}\right)^{-1} \int_0^{h^*} f(\beta_{l^*}(t)) \frac{\partial \beta_{l^*}(t)}{\partial \alpha}\, dt.$$

Since $\frac{\partial \beta_{l^*}(t)}{\partial \alpha} = \frac{\partial}{\partial \alpha}\left[\frac{\alpha l^*}{\alpha l^* + (t + xh^*)(dl^* + c)}\right] = \frac{l^*(t + xh^*)(dl^* + c)}{(\alpha l^* + (t + xh^*)(dl^* + c))^2} > 0$ and at a stable equilibrium $\frac{\partial \Phi(l)}{\partial l} < 1$, it follows that $\frac{dl^*}{d\alpha} > 0$.

$$\frac{dF(\beta_{l^*}(t))}{d\alpha} = \frac{\partial F(\beta_{l^*}(t))}{\partial \beta} \frac{\partial \beta_{l^*}(t)}{\partial l} \frac{dl^*}{d\alpha} = f(\beta_{l^*}(t)) \frac{\partial \beta_{l^*}(t)}{\partial l} \frac{dl^*}{d\alpha} > 0,$$

because $\frac{\partial \beta_{l^*}(t)}{\partial l} = \frac{\partial}{\partial l}\left[\frac{\alpha l^*}{\alpha l^* + (t + xh^*)(dl^* + c)}\right] = \frac{\alpha c(t + xh^*)}{(\alpha l^* + (t + xh^*)(dl^* + c))^2} > 0$ and $\frac{dl^*}{d\alpha} > 0$.

Combining $\frac{dl^*}{d\alpha} > 0$ and $\frac{dF(\beta_{l^*}(t))}{d\alpha} > 0$, we conclude that $\frac{dY}{d\alpha} < 0$. □

B.4 Proof of Theorem 2.4

Introduction of $\tau < 1$ changes the 2^{nd} period employee's payoffs in the following way:

- HL strategy: $(t + xh^*)(\tau - d(l^* + h^*) - 2c) + (1 - \tau)t$
- H strategy: $(t + xh^*)(\tau - dh^* - c) + (1 - \tau)t + \alpha l^*$
- ND strategy: $t + \alpha l^*$,

while the 1st period payoffs remain the same. Therefore, the employee will prefer the HL strategy if and only if:

$$\beta((t + xh^*)(\tau - d(l^* + h^*) - 2c) + (1 - \tau)t) + \alpha l^* \geq$$

$$\beta((t + xh^*)(\tau - dh^* - c) + (1 - \tau)t + \alpha l^*) \Leftrightarrow$$

$$t \leq \frac{1 - \beta}{\beta} \frac{\alpha l^*}{dl^* + c} - xh^*.$$

An employee will prefer the ND strategy if and only if:

$$t \geq (t + xh^*)(\tau - dh^* - c) + (1 - \tau)t \Leftrightarrow$$

$$t \geq \frac{xh^*(\tau - dh^* - c)}{dh^* + c}.$$

We consider small decreases of τ from 1, therefore the condition to have an interior stable equilibrium $l^* > 0$ is $x\tau - xc - c > 0$, and h^* is found as before:

$$h^* = \min\{\frac{x\tau - xc - c}{d(1+x)}, 1].\}$$

We repeat the computation of Y under the $\tau < 1$ policy:

$$\begin{aligned}
Y &= \int_0^{h^*}\int_0^{\beta_{l^*}(t)} f(\beta)[(t+xh^*)(\tau - d(h^*+l^*) - 2c) + (1-\tau)t]\,d\beta\,dt \\
&+ \int_0^{h^*}\int_{\beta_{l^*}(t)}^1 f(\beta)[(t+xh^*)(\tau - dh^* - c) + (1-\tau)t]\,d\beta\,dt \\
&+ \int_{h^*}^1\int_0^1 f(\beta)t\,d\beta\,dt \\
&= \int_0^{h^*} F(\beta_{l^*}(t))[(t+xh^*)(\tau - d(h^*+l^*) - 2c) + (1-\tau)t]\,dt \\
&+ \int_0^{h^*} (1 - F(\beta_{l^*}(t)))[(t+xh^*)(\tau - dh^* - c) + (1-\tau)t]\,dt + \int_{h^*}^1 t\,dt.
\end{aligned}$$

Simplifying and substituting $h^* = \dfrac{\tau x - xc - c}{d(1+x)}$ gives:

$$Y = \frac{d^2(1+x)^3 + x(c - \tau x + cx)^2}{2d^2(1+x)^3} - \int_0^{h^*} F(\beta_{l^*}(t))(t+xh^*)(dl^*+c)\,dt.$$

Let

$$Y_1 = \frac{d^2(1+x)^3 + x(c - \tau x + cx)^2}{2d^2(1+x)^3} \text{ and } Y_2 = -\int_0^{h^*} F(\beta_{l^*}(t))(t+xh^*)(dl^*+c)\,dt$$

and compute $\dfrac{dY}{d\tau} = \dfrac{dY_1}{d\tau} + \dfrac{dY_2}{d\tau}$.

$$\frac{dY_1}{d\tau} = \frac{x(-c - cx + \tau x)(-c - cx + 3\tau x)}{2d^2(1+x)^3} > 0,$$

because $x\tau - xc - c > 0$.

$$\begin{aligned}
\frac{dY_2}{d\tau} &= - \int_0^{h^*} [\frac{dF(\beta_{l^*}(t))}{d\tau}(t+xh^*)(dl^*+c) \\
&+ F(\beta_{l^*}(t))\left(\frac{dh^*}{d\tau}x(dl^*+c) + \frac{dl^*}{d\tau}d(t+xh^*)\right)]\,dt \\
&- \frac{dh^*}{d\tau}F(\beta_{l^*}(h^*))h^*(1+x)(dl^*+c).
\end{aligned}$$

In order to determine the sign of the expression above, consider $\frac{dh^*}{d\tau}$, $\frac{dl^*}{d\tau}$, and $\frac{dF(\beta_{l^*}(t))}{d\tau}$:

$$\begin{aligned}
\frac{dh^*}{d\tau} &= \frac{x}{d(1+x)} > 0. \\
\frac{dl^*}{d\tau} &= \frac{d}{d\tau}\int_0^{h^*} F(\beta_{l^*}(t))\,dt = \int_0^{h^*} \frac{dF(\beta_{l^*}(t))}{d\tau}\,dt + \frac{dh^*}{d\tau}F(\beta_{l^*}(h^*)) \\
&= \int_0^{h^*} \frac{\partial F(\beta_{l^*}(t))}{\partial \beta}\frac{\partial \beta_{l^*}(t)}{\partial l}\frac{dl^*}{d\tau}\,dt + \frac{dh^*}{d\tau}F(\beta_{l^*}(h^*)) \Rightarrow \\
\frac{dl^*}{d\tau} &= \left(1 - \frac{\partial \Phi(l)}{\partial l}\right)^{-1}\left(\frac{dh^*}{d\tau}F(\beta_{l^*}(h^*))\right) > 0,
\end{aligned}$$

since we are considering a stable equilibrium. Finally,

$$\frac{dF(\beta_{l^*}(t))}{d\tau} = \frac{\partial F(\beta_{l^*}(t))}{\partial \beta}\frac{\partial \beta_{l^*}(t)}{\partial l}\frac{dl^*}{d\tau} = f(\beta_{l^*}(t))\frac{\partial \beta_{l^*}(t)}{\partial l}\frac{dl^*}{d\tau} > 0,$$

since $\frac{\partial \beta_{l^*}(t)}{\partial l} > 0$. Therefore, we conclude that $\frac{dY_2}{d\tau} < 0$, and the sign of $\frac{dY}{d\tau} = \frac{dY_1}{d\tau} + \frac{dY_2}{d\tau}$ is indeterminant. A sufficient condition for it to be negative (i.e. $\tau < 1$ policy to be beneficial) is:

$$\begin{aligned}
&\int_0^{h^*}\left[F(\beta_{l^*}(t))\left(\frac{dh^*}{d\tau}x(dl^*+c) + \frac{dl^*}{d\tau}d(t+xh^*)\right)\right]dt \\
&\qquad + \frac{dh^*}{d\tau}F(\beta_{l^*}(h^*))h^*(1+x)(dl^*+c) > \frac{x(-c-cx+\tau x)(-c-cx+3\tau x)}{2d^2(1+x)^3},
\end{aligned}$$

which holds for sufficiently present-biased $F(\beta)$.

□

B.5 Equilibrium Stability for Sophisticated Employees

A stable interior equilibrium must be robust to small perturbation. The following if the dynamic system corresponding to the movements around the fixed points, defined by equations (2.4) and (2.5):

$$\begin{cases} \dot{h} &= H(h,l) - h \\ \dot{l} &= L(h,l) - l, \end{cases}$$

and the equilibrium is stable if and only if all eigenvalues of the Jacobian:

$$J = \begin{pmatrix} (\frac{\partial H}{\partial h} - 1) & \frac{\partial H}{\partial l} \\ \frac{\partial L}{\partial h} & (\frac{\partial L}{\partial l} - 1) \end{pmatrix},$$

have negative real parts. The eigenvalues are found to be

$$\lambda_{1,2} = \frac{1}{2}\left(\frac{\partial H}{\partial h} + \frac{\partial L}{\partial l} - 2 \pm \sqrt{\mathcal{D}}\right),$$

where $\mathcal{D} = (\frac{\partial H}{\partial h} + \frac{\partial L}{\partial l} - 2)^2 - 4((\frac{\partial H}{\partial h} - 1)(\frac{\partial L}{\partial l} - 1) - \frac{\partial H}{\partial l}\frac{\partial L}{\partial h})$, and both have negative real parts if and only if $\lambda_1\lambda_2 > 0$ and $\lambda_1 + \lambda_2 < 0$. This is equivalent to the following necessary and sufficient conditions for stability:

$$\left(\frac{\partial H}{\partial h} - 1\right)\left(\frac{\partial L}{\partial l} - 1\right) - \frac{\partial H}{\partial l}\frac{\partial L}{\partial h} > 0 \text{ and}$$
$$\frac{\partial H}{\partial h} + \frac{\partial L}{\partial l} - 2 < 0.$$

□

B.6 Proof of Theorem 2.5

Differentiate equations (2.4) and (2.5) with respect to a:

$$\begin{cases} \dfrac{dh}{da} = \dfrac{\partial H}{\partial h}\dfrac{dh}{da} + \dfrac{\partial H}{\partial l}\dfrac{dl}{da} + \dfrac{\partial H}{\partial a} \\ \dfrac{dl}{da} = \dfrac{\partial L}{\partial h}\dfrac{dh}{da} + \dfrac{\partial L}{\partial l}\dfrac{dl}{da} + \dfrac{\partial L}{\partial a} \end{cases}$$

Rearranging, we get:

$$\begin{cases} \left(1 - \dfrac{\partial H}{\partial h}\right)\dfrac{dh}{da} - \dfrac{\partial H}{\partial l}\dfrac{dl}{da} = \dfrac{\partial H}{\partial a} \\ -\dfrac{\partial L}{\partial h}\dfrac{dh}{da} + \left(1 - \dfrac{\partial L}{\partial l}\right)\dfrac{dl}{da} = \dfrac{\partial L}{\partial a} \end{cases}$$

Let

$$D = \begin{vmatrix} 1 - \dfrac{\partial H}{\partial h} & -\dfrac{\partial H}{\partial l} \\ -\dfrac{\partial L}{\partial h} & 1 - \dfrac{\partial L}{\partial l} \end{vmatrix}, \quad D_h = \begin{vmatrix} \dfrac{\partial H}{\partial a} & -\dfrac{\partial H}{\partial l} \\ \dfrac{\partial L}{\partial a} & 1 - \dfrac{\partial L}{\partial l} \end{vmatrix}, \quad D_l = \begin{vmatrix} 1 - \dfrac{\partial H}{\partial h} & \dfrac{\partial H}{\partial a} \\ -\dfrac{\partial L}{\partial h} & \dfrac{\partial L}{\partial a} \end{vmatrix}.$$

Then by Cramer's rule, $\dfrac{dh}{da} = \dfrac{D_h}{D}$ and $\dfrac{dl}{da} = \dfrac{D_l}{D}$. From stability condition (2.6) we conclude that $D > 0$ at a stable equilibrium.

Next we show that $D_h < 0$ whenever $D_l > 0$, i.e. we show that the condition for $\dfrac{dh}{da} < 0$ is weaker than for $\dfrac{dl}{da} > 0$. It is convenient to denote $m = -\dfrac{\partial H}{\partial a}/\dfrac{\partial L}{\partial a}$, which represents the relative change in the present-bias of agents with high productivity type (agents who are likely to use the commitment strategy in period 0) compared to lower productivity type (agents who are likely to engage in both types of e-mail). In addition, $m > 0$, because:

$$\frac{\partial H}{\partial a} = -\int_{t_c}^{t_n} \frac{\partial F(\beta_{h^*,l^*}(t))}{\partial a}\,dt < 0,$$
$$\frac{\partial L}{\partial a} = \int_{0}^{t_c} \frac{\partial F(\beta_{h^*,l^*}(t))}{\partial a}\,dt > 0.$$

Using m, condition $D_h < 0$ becomes:

$$1 - \frac{\partial L}{\partial l} > \frac{1}{m}\frac{\partial H}{\partial l},$$

and condition $D_l > 0$ becomes:

$$1 - \frac{\partial H}{\partial h} > m\frac{\partial L}{\partial h}.$$

Since $\dfrac{\partial t_c}{\partial l} < 0$ and $\dfrac{\partial \beta_{h^*,l^*}(t)}{\partial l} > 0$, we have

$$\frac{\partial H}{\partial l} = \frac{\partial t_c}{\partial l} F(\beta_{h^*,l^*}(t_c)) - \int_{t_c}^{t_n} f(\beta_{h^*,l^*}(t)) \frac{\partial \beta_{h^*,l^*}(t)}{\partial l}\, dt < 0,$$

and conclude that $D_h < 0$ whenever $\dfrac{\partial L}{\partial l} \leq 1$. When $\dfrac{\partial L}{\partial l} > 1$ and $D_l > 0$ we combine the inequalities to get:

$$\left(1 - \frac{\partial L}{\partial l}\right)\left(1 - \frac{\partial H}{\partial h}\right) < m\frac{\partial L}{\partial h}\left(1 - \frac{\partial L}{\partial l}\right).$$

Then, using condition (2.6), we derive that

$$\frac{\partial H}{\partial l}\frac{\partial L}{\partial h} < m\frac{\partial L}{\partial h}\left(1 - \frac{\partial L}{\partial l}\right).$$

Thus, in order to get $D_h < 0$, it is left to show that $\dfrac{\partial L}{\partial h} > 0$. This is true, because if $\dfrac{\partial L}{\partial l} > 1$, by condition (2.7) we get $\dfrac{\partial H}{\partial h} < 1$, and for condition (2.6) to hold we must have $\dfrac{\partial L}{\partial h} > 0$, because $\dfrac{\partial H}{\partial l} < 0$. This establishes the fact that the condition for $D_l > 0$ is stronger than for $D_h < 0$.

We proceed with deriving conditions when $D_l > 0$. It is sufficient to have $1 - \frac{\partial H}{\partial h} > 0$ and $\frac{\partial L}{\partial h} < 0$, since $m > 0$. In addition, for an arbitrary $\frac{\partial F(\beta)}{\partial a}$, these two conditions are necessary, since m can take any positive value. Expanding $\frac{\partial H}{\partial h}$ and $\frac{\partial L}{\partial h}$, we get:

$$\begin{aligned} 1 - \frac{\partial H}{\partial h} &= 1 - \frac{\partial t_n}{\partial h}(1 - F(\beta(t_n)) - \frac{\partial t_c}{\partial h}F(\beta(t_c)) + \int_{t_c}^{t_n} f(\beta(t))\frac{\partial \beta}{\partial h}dt, \text{ and} \\ \frac{\partial L}{\partial h} &= \frac{\partial t_c}{\partial h}F(\beta(t_c)) + \int_0^{tc} f(\beta(t))\frac{\partial \beta}{\partial h}dt. \end{aligned}$$

Therefore, the two sufficient conditions hold when

$$\frac{\partial t_c}{\partial h} < M, \tag{B.1}$$

where

$$M = \frac{1}{F(\beta(t_c))}\min\{1 - \frac{\partial t_n}{\partial h}(1 - F(\beta(t_n)) + \int_{t_c}^{t_n} f(\beta(t))\frac{\partial \beta}{\partial h}dt, - \int_0^{tc} f(\beta(t))\frac{\partial \beta}{\partial h}dt\}.$$

Substituting the expression for $\frac{\partial t_c}{\partial h}$ in the condition (B.1) we get:

$$-\left(1 - \frac{2c + dl}{(2c + d(h+l))^2}\right)x < M.$$

It is intuitive that as x increases, more people choose to check e-mail. Formally,

$$\frac{\partial h}{\partial x} = \frac{\partial t_n}{\partial x}(1 - F(\beta(t_n)) + \frac{\partial t_c}{\partial x}F(\beta(t_c)) - \int_{t_c}^{t_n} f(\beta(t))\frac{\partial \beta}{\partial x}dt < 0,$$

since $\frac{\partial t_n}{\partial x} > 0$, $\frac{\partial t_c}{\partial x} > 0$, and $\frac{\partial \beta}{\partial x} > 0$. Therefore, as x increases, we can guarantee that h is high enough to have $\frac{\partial t_c}{\partial h} < 0$, in which case we can continue to increase x to guarantee condition (B.1). Thus, for $D_l > 0$ it is sufficient to have $x > \underline{x}$, for some $\underline{x}$. $\square$

B.7 Proof of Theorem 2.6

The introduced $\tau < 1$ policy changes strategy cutoffs in h, l-equilibrium as follows:

$$t_c \stackrel{\text{def}}{=} \frac{xh(\tau - d(l+h) - 2c)}{d(l+h) + 2c},$$
$$t_n \stackrel{\text{def}}{=} \frac{xh(\tau - dh - c)}{dh + c}.$$

Differentiate equations (2.4) and (2.5) with respect to τ:

$$\frac{\partial H}{\partial \tau} = \frac{\partial t_n}{\partial \tau}(1 - F(\beta_{h^*,l^*}(t_n))) - \frac{\partial t_c}{\partial \tau} F(\beta_{h^*,l^*}(t_c)),$$
$$\frac{\partial L}{\partial \tau} = \frac{\partial t_c}{\partial \tau} F(\beta_{h^*,l^*}(t_c)).$$

Since $\dfrac{\partial t_c}{\partial \tau} > 0$, $\dfrac{\partial l}{\partial \tau} > 0$. In addition, $\dfrac{\partial h}{\partial \tau} < 0$ if and only if:

$$\frac{\partial t_n}{\partial \tau} < \frac{\partial t_n}{\partial \tau} F(\beta_{h^*,l^*}(t_n)) + \frac{\partial t_c}{\partial \tau} F(\beta_{h^*,l^*}(t_c)),$$

i.e. if $F(\beta)$ is relatively large (present-biased), since $\dfrac{\partial t_n}{\partial \tau} > 0$ also. In order to demonstrate the potential benefit of $\tau < 1$ policy, consider the derivative of the firm's output Y with respect to τ:

$$\frac{dY}{d\tau} = \frac{\partial Y}{\partial \tau} + \frac{\partial Y}{\partial h}\frac{\partial h}{\partial \tau} + \frac{\partial Y}{\partial l}\frac{\partial l}{\partial \tau}. \tag{B.2}$$

The output function under the policy with $\tau < 1$ is

$$\begin{aligned} Y &= -\int_0^{t_c} F(\beta_{h^*,l^*}(t))[(t + xh^*)(dl^* + c)]dt \\ &+ \int_{t_c}^{t_n} F(\beta_{h^*,l^*}(t))[\tau t - (t + xh^*)(\tau - dh^* - c)]dt \\ &+ \frac{1}{2}\left(1 + \frac{x^2(h^*)^2(\tau - c - dh^*)^2}{c + dh^*}\right). \end{aligned}$$

Consider first the direct effect of the change in policy on the output:

$$
\begin{aligned}
\frac{\partial Y}{\partial \tau} &= -\frac{\partial t_c}{\partial \tau} F(\beta_{h^*,l^*}(t_c))[(t_c + xh^*)(dl^* + c)] + \int_{t_c}^{t_n} F(\beta_{h^*,l^*}(t))(t - (t + xh^*))dt \\
&+ \frac{\partial t_n}{\partial \tau} F(\beta_{h^*,l^*}(t_n))[\tau t_n - (t_n + xh^*)(\tau - dh^* - c)] \\
&- \frac{\partial t_c}{\partial \tau} F(\beta_{h^*,l^*}(t_c))[\tau t_c - (t_c + xh^*)(\tau - dh^* - c)] \\
&+ \frac{x^2(h^*)^2(\tau - dh^* - c)}{dh^* + c} = \\
&\quad \text{By the definition of } t_c \text{ and } t_n, \text{ at } \tau = 1 \\
&= -\int_{t_c}^{t_n} F(\beta_{h^*,l^*}(t))(xh^*)dt + \frac{x^2(h^*)^2(1 - dh^* - c)}{dh^* + c},
\end{aligned}
$$

which is positive even when $F(.)$ is large. Since $F(\beta)$ is bounded by 1,

$$
\begin{aligned}
\left.\frac{\partial Y}{\partial \tau}\right|_{\tau=1} &\geq -xh^* \frac{h(c + dl^*)x}{(c + dh^*)(2c + d(h^* + l^*))} + \frac{x^2(h^*)^2(1 - dh^* - c)}{dh^* + c} \\
&= (h^* x^*)^2 \frac{1 - dh^* - dl^* - 2c}{dh^* + dl^* + 2c} > 0.
\end{aligned}
$$

Therefore, the direct effect of the policy on output is negative, and this is because sophisticates make correct choices given their preferences and thus an extra constraint in the form of policy does not improve the output. Next, we consider the indirect effects of the policy though the changes in the equilibrium amounts of l-mail and h-mail.

$$
\begin{aligned}
\frac{\partial Y}{\partial h} &= -\int_0^{t_c} F(\beta_{h^*,l^*}(t))(dl^* + c)dt + \int_{t_c}^{t_n} F(\beta_{h^*,l^*}(t))[d(t + 2xh) + x(c - \tau)]dt \\
&+ \frac{1}{2} h^* x^2 \left(2c + 3dh^* - 4\tau + \frac{(2c + dh^*)\tau^2}{(c + dh^*)^2}\right).
\end{aligned}
$$

When the population of employees becomes very present biased, i.e. $F(\beta) \approx 1$, the expression above, evaluated at $\tau = 1$ becomes

$$
\frac{h(-1 + 2c + d(h^* + l^*))x}{2(2c + d(h^* + l^*))^2} A,
$$

where

$$
\begin{aligned}
A &= 4c^2(1 + x) + d(-(h^* + 2l^*)x + d(h^* + l^*)(2l^* + 3h^* x)) \\
&+ 2c(-2x + d(h^* + 4h^* x + l^*(3 + x))),
\end{aligned}
$$

and since $(-1 + 2c + d(h^* + l^*)) < 0$, it is positive if and only if $A < 0$. For large x we can just look at the overall sign of the terms that contain x, i.e. $A < 0$ for large x if and only if $B < 0$, where

$$
\begin{aligned}
B &= -4c + 4c^2 - dh^* + 8cdh^* + 3d^2(h^*)^2 - 2dl^* + 2cdl^* + 3d^2 h^* l^* \\
&= -(1 - dh^* - dl^* - 2c)(4c + dh^*) - 4c^2 - 2cdl^* + 2dl^2 - 2dh^*(dh^* + dl^* + 2c) \\
&< -(4c + dh^*) - 4c^2 - 2cdl^* + 2dl^2 - 2dh^* < 0,
\end{aligned}
$$

because $l^* \leq h^*$. Therefore, we conclude that $\dfrac{\partial Y}{\partial h} > 0$ for a sufficiently present-biased population and for the large x.

Finally, we consider the derivative of the output with respect to l:

$$\frac{\partial Y}{\partial h} = -\int_0^{t_c} F(\beta_{h^*,l^*}(t))d(t + xh^*)dt < 0.$$

Combining the results above, namely that $\dfrac{\partial Y}{\partial \tau} > 0$, $\dfrac{\partial Y}{\partial h} > 0$, $\dfrac{\partial h}{\partial \tau} < 0$, $\dfrac{\partial Y}{\partial l} < 0$, and $\dfrac{\partial l}{\partial \tau} > 0$, and noting that the high present bias and large x make the last two terms in equation (B.2) dominant, we conclude that in this case $\dfrac{dY}{d\tau} < 0$, and restrictive $\tau < 1$ policy is beneficial for the firm. □

B.8 Proof of Theorem 2.7

Compute the partial derivatives:

$$\frac{\partial H}{\partial \alpha} = -\int_{t_c}^{t_n} f(\beta_{h^*,l^*}(t))\frac{\partial \beta_{h^*,l^*}(t)}{\partial \alpha}\,dt$$
$$\frac{\partial L}{\partial \alpha} = \int_0^{t_c} f(\beta_{h^*,l^*}(t))\frac{\partial \beta_{h^*,l^*}(t)}{\partial \alpha}\,dt.$$

Since $\dfrac{\partial \beta_{h^*,l^*}(t)}{\partial \alpha} > 0$, we have $\dfrac{\partial H}{\partial \alpha} < 0$ and $\dfrac{\partial L}{\partial \alpha} > 0$.

Considering the derivative of the output function with respect to α, we get that

$$\frac{dY}{d\alpha} = \frac{\partial Y}{\partial \alpha} + \frac{\partial Y}{\partial h}\frac{\partial h}{\partial \alpha} + \frac{\partial Y}{\partial l}\frac{\partial l}{\partial \alpha}.$$

Following the derivation in Theorem 2.6, and noting that $\dfrac{\partial Y}{\partial \alpha} = 0$, we conclude that whenever the distribution of workers is sufficiently present-biased and x is large enough, we have $\dfrac{dY}{d\alpha} < 0$, i.e. a firm would benefit from a monitoring strategy. □

B.9 Proof of Theorem 2.8

Conditions that characterize stability of an equilibrium with time consistent agents are derived similarly to the conditions for sophisticated agents and are the following:

$$\left(\frac{\partial H}{\partial h} - 1\right)\left(\frac{\partial L}{\partial l} - 1\right) - \frac{\partial H}{\partial l}\frac{\partial L}{\partial h} > 0 \text{ and} \tag{B.3}$$
$$\frac{\partial H}{\partial h} + \frac{\partial L}{\partial l} - 2 < 0. \tag{B.4}$$

Again, parallel to the derivation of comparative statics result for sophisticates, we use Cramer's rule on the dynamic system corresponding to the movements around the fixed points of fixed-point equations to conclude that if

$$D = \begin{vmatrix} (1 - \frac{\partial H}{\partial h}) & -\frac{\partial H}{\partial l} \\ -\frac{\partial L}{\partial h} & (1 - \frac{\partial L}{\partial l}) \end{vmatrix},\ D_h = \begin{vmatrix} \frac{\partial H}{\partial a} & -\frac{\partial H}{\partial l} \\ \frac{\partial L}{\partial a} & (1 - \frac{\partial L}{\partial l}) \end{vmatrix},\ D_l = \begin{vmatrix} (1 - \frac{\partial H}{\partial h}) & \frac{\partial H}{\partial a} \\ -\frac{\partial L}{\partial h} & \frac{\partial L}{\partial a} \end{vmatrix},$$

then $D > 0$ by stability and $\frac{\partial h}{\partial a} > 0$ if and only if $D_h > 0$ and $\frac{\partial l}{\partial a} > 0$ if and only if $D_l > 0$. Next we show the first part of the theorem, specifically that $D_h > 0$ whenever $D_l > 0$. Let $m = \frac{\partial H}{\partial a} / \frac{\partial L}{\partial a}$. Then $m > 0$, because

$$\frac{\partial H}{\partial a} = \int_{t_0}^{1} \frac{\partial F(\delta_0(t))}{\partial a}\, dt > 0$$
$$\frac{\partial L}{\partial a} = \int_{0}^{t_0} \frac{\partial F(\delta_1(t))}{\partial a}\, dt + \int_{t_0}^{1} \frac{\partial F(\delta_0(t))}{\partial a}\, dt > 0.$$

In addition, note that

$$\frac{\partial H}{\partial l} = \int_{t_0}^{1} \frac{\partial F(\delta_0(t))}{\partial l}\, dt = \int_{t_0}^{1} f(\delta_0(t)) \frac{\partial \delta_0(t)}{\partial l}\, dt > 0,$$

because we can expand $\frac{\partial \delta_0(t)}{\partial l}$ to see that $\frac{\partial \delta_0(t)}{\partial l} > 0$ for $t > t_0$. If $\frac{\partial L}{\partial l} \leq 1$ then $D_h \geq 0$, because $\frac{\partial H}{\partial l} > 0$ implies that

$$1 - \frac{\partial L}{\partial l} > -\frac{1}{m} \frac{\partial H}{\partial l}.$$

On the other hand, if $\frac{\partial L}{\partial l} > 1$ and $D_l > 0$, then by the stability condition, we know that $\frac{\partial H}{\partial h} < 1$ and therefore we must have $\frac{\partial L}{\partial h} < 0$. Multiply $D_l > 0$ inequality by $\left(1 - \frac{\partial L}{\partial l}\right)$ to get

$$\left(1 - \frac{\partial H}{\partial h}\right)\left(1 - \frac{\partial L}{\partial l}\right) < -m \left(1 - \frac{\partial L}{\partial l}\right) \frac{\partial L}{\partial h}.$$

Using another stability condition this implies that

$$\frac{\partial H}{\partial l} \frac{\partial L}{\partial h} < -m \frac{\partial L}{\partial h} \left(1 - \frac{\partial L}{\partial l}\right) \Rightarrow$$
$$D_h > 0.$$

Thus, we have shown that in any stable equilibrium, $\frac{\partial h}{\partial a} > 0$ whenever $\frac{\partial l}{\partial a} > 0$. The condition for $\frac{\partial l}{\partial a} > 0$ is equivalent to $D_l > 0$, which is equivalent to

$$\left(1 - \frac{\partial H}{\partial h}\right) > -\frac{\partial L}{\partial h} m.$$

Expanding the above we see that it is equivalent to

$$1 - \frac{\partial t_0}{\partial h}(1 - F(\delta_0(t_0))) > (1 - m) \int_{t_0}^{1} f(\delta_0(t)) \frac{\partial \delta_0(t)}{\partial h}\, dt - m \int_{0}^{t_0} f(\delta_1(t)) \frac{\partial \delta_1(t)}{\partial h}\, dt.$$

Substituting m and rearranging, we find that it is equivalent to

$$\frac{\partial H}{\partial a}\left(1 + \int_{0}^{t_0} f(\delta_1(t)) \frac{\partial \delta_1(t)}{\partial h}\, dt\right) + \int_{0}^{t_0} f(\delta_1(t)) \frac{\partial \delta_1(t)}{\partial a}\, dt \left(1 - \int_{t_0}^{1} f(\delta_0(t)) \frac{\partial \delta_0(t)}{\partial h}\, dt\right) >$$
$$\frac{\partial t_0}{\partial h}(1 - F(\delta_0(t_0)))\left(\frac{\partial H}{\partial a} + \int_{0}^{t_0} f(\delta_1(t)) \frac{\partial \delta_1(t)}{\partial a}\, dt\right).$$

We note that $\dfrac{\partial \delta_1(t)}{\partial a} > 0$. In addition, since $\dfrac{\partial H}{\partial a} > 0$, $\int_0^{t_0} f(\delta_1(t))\dfrac{\partial \delta_1(t)}{\partial h}\,dt < 1$, and $F(\delta_0(t_0)) < 1$, the following are two sufficient conditions that would guarantee that $D_l > 0$:

$$\frac{\partial t_0}{\partial h} < 0 \tag{B.5}$$

$$\frac{\partial \delta_0(t)}{\partial h} < 0 \text{ for } t > t_0, \tag{B.6}$$

which simplify to

$$\begin{aligned} &c < (dh+c)^2 \\ &c < 3cdh + 2c^2 + d^2h^2 + d^2hl + cdl. \end{aligned}$$

Since the first condition is more restrictive, it by itself is sufficient. It holds whenever the equilibrium amount of h-mail is above some small threshold $\bar{h}$. □

B.10 Proof of Theorem 2.9

Before doing the comparative statics analysis to see the effect of reducing τ, we rederive the strategies of time consistent agents under such policy. Given the equilibrium values for h and l, in period 1, agents choose strategy HL if and only if

$$\delta < \frac{\alpha l}{\alpha l + (t + xh)(dl + c)} \stackrel{\text{def}}{=} \delta_1(t).$$

In period 0, if expect to only check H-mail, then turn e-mail on if and only if

$$t < \frac{xh(\tau - dh - c)}{dh + c} \stackrel{\text{def}}{=} t_0,$$

and if expect to check HL-mail, then turn e-mail on if and only if

$$t < \frac{\frac{1-\delta}{\delta}\alpha l + xh(\tau - d(l+h) - 2c)}{d(l+h) + 2c} \Leftrightarrow$$

$$\delta < \frac{\alpha l}{\alpha l + (t + xh)(d(l+h) + 2c) - \tau x h} \stackrel{\text{def}}{=} \delta_0(t).$$

In modeling the firm's utility function, there is a choice in what should be the firm's discount factor. In β, δ-model it was natural to assume that the firm is fully time consistent, i.e. its $\beta = 1$. The similar assumption (i.e. $\delta = 1$) might be justifiable for a firm in case of time consistent employees. It would mean that in general the firm's workers are more impatient that the actual firm; however, this assumption is not necessarily intuitive and is hard to justify. Alternatively, we may assume that the firm is just the sum of its workers and its discount level is not different. Below we write down the expressions for both cases and we will see that for analytical results the difference between the two assumptions is not important. First, assuming that the firm is just a sum of its employees, its utility function can be written as follows:

$$\begin{aligned} Y = &\int_0^{t_0}\int_0^1 \delta^2 f(\delta)[-t(dh+c) + xh(\tau - dh - c)]\,d\delta\,dt - \int_0^{t_0}\int_0^{\delta_1} \delta^2 f(\delta)[(t+xh)(dl+c)]\,d\delta\,dt \\ &+ \int_{t_0}^1\int_0^{\delta_0} \delta^2 f(\delta)[-t(d(l+h)+2c) + xh(\tau - d(l+h) - 2c)]\,d\delta\,dt + \int_0^1\int_0^1 \delta^2 f(\delta) t\,d\delta\,dt. \end{aligned}$$

Since we make no assumption on the the density of δ - $f(\delta)$, it can absorb (with a scaling factor) the firm's own discounting δ, in which case for the expression above is just an affine transformation of the firm's utility function, when firm's $\delta = 1$:

$$Y_{\delta=1} = \int_0^{t_0} -t(dh+c)\,dt - \int_0^{t_0} F(\delta_1(t))[(t+xh)(dl+c)]\,dt +$$
$$\int_{t_0}^1 F(\delta_0(t))[-t(d(l+h)+2c) + xh(\tau - d(l+h) - 2c)\ \ dt + t_0 xh(\tau - dh - c) + \frac{1}{2}.$$

It is easily seen that the firm gains more from employees who only engage in H-mail than from employees who do both types of e-mail. Therefore, as before the firm would like to implement a policy that reduces the equilibrium amount of l-mail. Next we show that in the first approximation, both the amount of h-mail and the amount of l-mail will decrease if the e-mail is restricted by $\tau < 1$ policy. Next, we use a similar comparative statics analysis as in Theorem 2.8 and replace derivatives with respect to a with derivatives with respect to τ. In the first approximation,

$$\frac{\partial H}{\partial \tau} = \frac{\partial t_0}{\partial \tau}(1 - F(\delta_0(t_0))) + \int_{t_0}^1 f(\delta_0(t))\frac{\partial \delta_0}{\partial \tau}\,dt > 0,$$
$$\frac{\partial L}{\partial \tau} = \frac{\partial t_0}{\partial \tau}F(\delta_1(t_0)) - \frac{\partial t_0}{\partial \tau}F(\delta_0(t_0)) + \int_0^{t_0} f(\delta_1(t))\frac{\partial \delta_1}{\partial \tau}\,dt + \int_{t_0}^1 f(\delta_0(t))\frac{\partial \delta_0}{\partial \tau}\,dt > 0.$$

The inequalities follow from $\frac{\partial t_0}{\partial \tau} > 0$, $\frac{\partial \delta_0}{\partial \tau} > 0$, $\frac{\partial \delta_1}{\partial \tau} = 0$, and $F(\delta_1(t_0)) = F(\delta_0(t_0))$. Therefore reducing τ has a negative effect on both H-mail and L-mail in the first approximation. To do full derivatives, we can repeat the Cramer rule derivation from the proof of Theorem 2.8 replacing a-derivatives with τ-derivatives. We find that whenever the decrease in τ leads to a decrease in the amount of l-mail, it also leads to the decrease in the amount of h-mail, which makes it unprofitable for the firm to restrict e-mail.

Moreover, restricting τ will lead to an increase in l-mail if $x > \bar{x}$ for some $\bar{x}$. To prove it, write down the condition that is equivalent to $\frac{dl}{d\tau} < 0$ or $D_l < 0$:

$$\left(1 - \frac{\partial H}{\partial h}\right)\frac{\partial L}{\partial \tau} + \frac{\partial H}{\partial \tau}\frac{\partial L}{\partial h} < 0.$$

This will hold whenever $\frac{\partial L}{\partial h} < 0$ and large. Recall that

$$\frac{\partial L}{\partial h} = \int_0^{t_0} f(\delta_1(t))\frac{\partial \delta_1}{\partial h}\,dt + \int_{t_0}^1 f(\delta_0(t))\frac{\partial \delta_0}{\partial h}\,dt.$$

From the proof of Theorem 2.8, this holds whenever x is larger than some threshold. □

B.11 Proof of Theorem 2.10

Compute the partial derivatives:

$$\frac{\partial H}{\partial \alpha} = \int_{t_0}^1 f(\delta_0(t))\frac{\partial \delta_0(t)}{\partial \alpha}\,dt$$
$$\frac{\partial L}{\partial \alpha} = \int_0^{t_0} f(\delta_1(t))\frac{\partial \delta_1(t)}{\partial \alpha}\,dt + \int_{t_0}^1 f(\delta_0(t))\frac{\partial \delta_0(t)}{\partial \alpha}\,dt.$$

It is easy to see that $\dfrac{\partial \delta_1(t)}{\partial \alpha} > 0$. Also, $\dfrac{\partial \delta_0(t)}{\partial \alpha} > 0$ for $t > t_0$, because

$$t > t_0 = \frac{xh(1 - dh - c)}{dh + c} > \frac{hx(1 - d(h + l) - 2c)}{d(h + l) + 2c}.$$

Therefore, $\dfrac{\partial H}{\partial \alpha} > 0$ and $\dfrac{\partial L}{\partial \alpha} > 0$. $\square$

Appendix C

Appendix for Chapter 3

C.1 Instructions

Thank you for agreeing to participate in this research experiment on group decision making. During the experiment, we will require your complete and undivided attention, so please refrain from distractions such as outside books, homework, and internet. We also ask you to turn off your cell phones. It is important that you do not talk or otherwise communicate with any other participants. Raise you hand if you have any questions and one of us will come to you. Now please pull out the dividers to either side of your chair as far as they go to assure your privacy as well as the privacy of the other participants.

In this experiment you will be given an opportunity to earn money. How much you earn will depend on your decisions and the decisions of other participants. During the experiment you will be accumulating points, which will be exchanged for money at the following rate: 25 points = $ 1.00. All earnings will be paid in cash at the end of the session. You will be paid anonymously (no other participant will be informed of your earnings).

Part 1

This part of the experiment will consist of 18 decision rounds. Before each round the computer will randomly divide you into pairs. Hence, in each round your group consists of yourself and 1 other participant. In addition, for each group the computer will toss a fair coin such that there is an equal chance of getting Heads or Tails. Your and your partner's payoff for the round will depend on the outcome of the coin toss AND on the action. Here is a sample payoff structure:

[SHOW sample payoff tables here initial screen shot for each round]

Each of you will be assigned a role of an S-player or an R-player. In each group exactly one player will be assigned an S-role and one player will be assigned an R-role. If you are an S-player, you will observe the outcome of the coin toss and will have an opportunity to communicate it to the R-player. As an S-player, you will send a message whether the outcome of the coin toss is Heads or Tails, however, you are not required to provide truthful information to the R-player. The R-player will not observe the actual outcome of the coin toss, only the S-player's message about it. Finally, the R-player will choose action A or action B. Your final payoff for the round will be realized and reported to you.

In order to familiarize you with the experiment will go through two practice rounds together. Please do not click or input any information until you are instructed to do so.

[To begin, please double-click on (z-leaf icon) on your desktop.] Remember that the first two rounds are the practice rounds, thus your payoff will not be counted towards the final earnings for the experiment. They will be followed by another 18 rounds with actual payoffs.

[Start practice rounds on server]

We are ready to begin. Each of you have been assigned a role [point out]. Here is the S-player's screen. Note that the outcome of the coin toss has been revealed to the S-player.

[slide]

And this is the R-player's screen. No information about the outcome of the coin toss is shown. If you are S-player, please select a message that is the same as your coin toss. If you are R-player, click OK.

[slide] [slide]

R-player now sees the message from S-player. If you are R-player, please select Action A. If you are S-player, click OK. Round summary and payoffs are then displayed to each player. [go through summary].

[slide]

Here are the round payoffs again for your reference. Please make sure you understand where your payoff is coming from. After you are done, please click OK to continue to the second practice round.

[Go through second practice round, now ask S-player to select opposite of his state and R-player select Action B]

Any questions?

Now we are going to complete a short quiz. Please answer all questions individually. If you have any questions, please raise your hand and one of us will come to assist you.

[start quiz]

We are now done with the quiz, and ready to begin Part 1 of the experiment.

[start part 2]

[DO PART 1 - 18 rounds]

Part 2

This part of the experiment will consist of 20 decision rounds. Now before each round the computer will randomly divide you into groups of three. Hence, in each round your group consists of yourself and 2 other participants. One participant in each group will be assigned an S-role and two participants will be assigned an R-role. Therefore, each of you will be randomly assigned a role of an S-player, R-player-1, or R-player-2. Just like before, for each group the computer will toss a fair coin such that there is an equal chance of getting Heads or Tails. If you are an R-player, your payoff will depend on the outcome of the coin toss AND your own action. If you are an S-player, your payoff will be determined as a sum of two numbers. The first number is calculated from the outcome of the coin toss AND action by R-player1. The second number is calculated from the outcome of the SAME coin toss AND action by R-player2. Here is a sample payoff structure:

[SHOW sample payoff tables here initial screen shot for each round]

If you are an S-player, you will observe the outcome of the coin toss and will have an opportunity to communicate it to the R-players. As an S-player, you will send the SAME message to both R-players whether the outcome of the coin toss is Heads or Tails. Again, S-player is not required to provide truthful information to the R-players. The R-players will not observe the actual outcome of the coin toss, only the S-players message about it.

Finally, the R-player1 will choose action A1 or action B1, and the R-player2 will choose action A2 or action B2. Your payoff for the round will then be reported to you.

Any questions? Again, we start with two practice rounds, and they will be followed by 20 paying rounds. Please do not start until you are instructed to do so.

[start practice rounds]

[explain round 1: S-player selects the same message as the coin toss, R-player1 selects Action A1, R-player 2 selects Action A2]

[explain round 2: S-player selects opposite message. R-player1 selects Action A1, R-player 2 selects Action B2]

Any questions?

[Go through practice screen shorts, announce instructions to click to proceed]

We are now ready to proceed to PART 2 of the experiment. Any final questions?

Now we are going to complete a short quiz. Please answer all questions individually. If you have any questions, please raise your hand and one of us will come to assist you.

[start quiz]

We are now done with the quiz, and ready to begin Part 2 of the experiment.

[start Part 2]

[DO PART 2 - 20 rounds]

This is the end of the experiment. You should now see a screen, which displays your total earnings in the experiment. Please record this on the Earnings row of your payment receipt sheet. Also enter $10.00 on the show-up fee row. Add the two numbers and enter the sum as the total.

We will pay each of you in private in the next room in the order of your Subject ID numbers. Remember you are under no obligation to reveal your earnings to the other players.

Please put the mouse behind the computer screen and do not use either the mouse or the keyboard at all. Please be patient and remain seated until we call you to be paid. Do not converse with the other participants or use your cell phone. Thank you for your cooperation.

Could the person with subject ID number 0 please go to the next room to be paid. Please bring all your belongings with you, including your payment receipt sheet.

C.2 Sample Screenshots

Please see Figure C.1 and Figure C.2 for sample screen shots in 2-person and 3-person games.

Figure C.1: Sample screenshot for a 2-person game

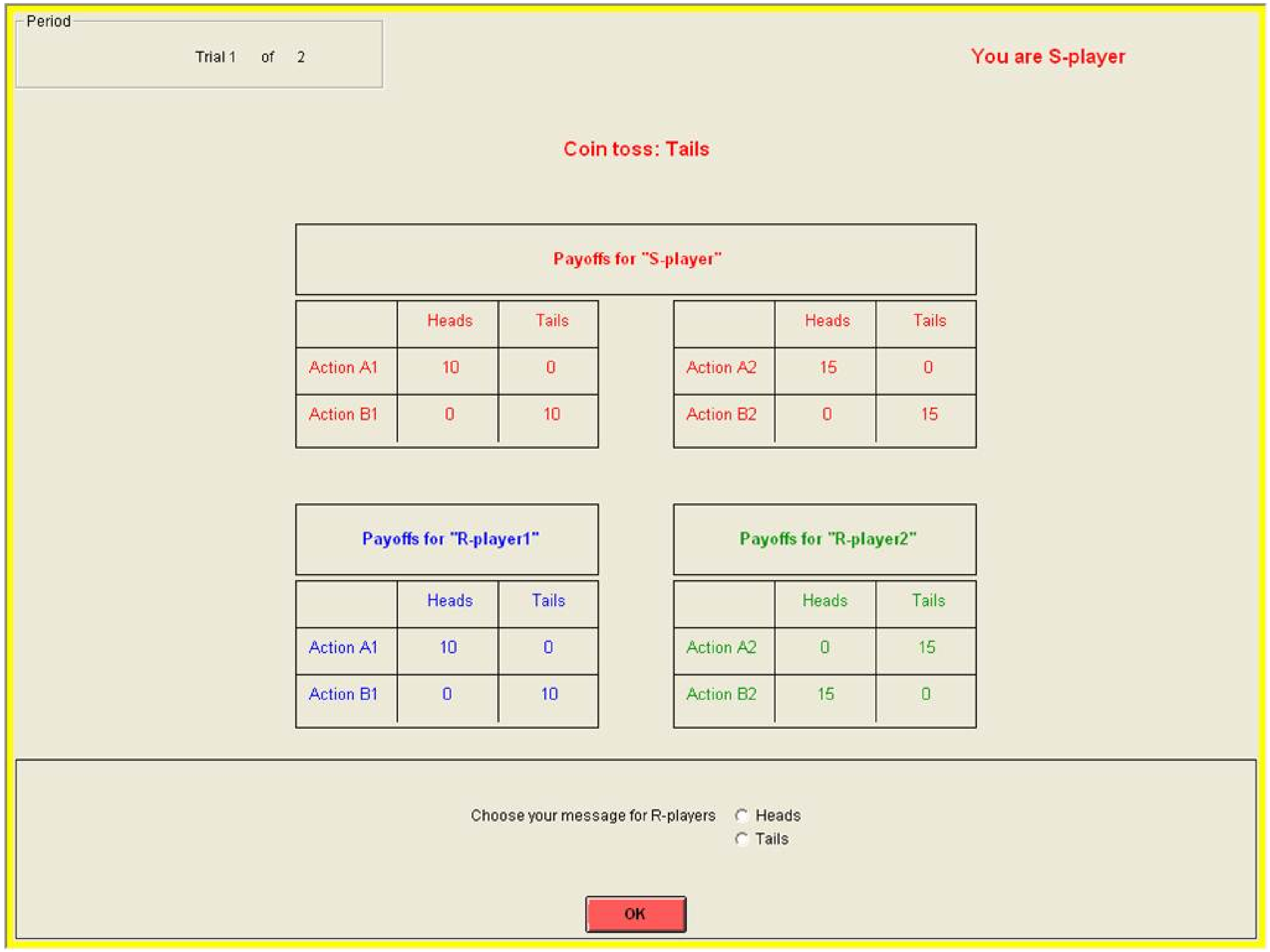

Figure C.2: Sample screenshot for a 3-person game

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