

A ROAD TO EFFICIENCY THROUGH COMMUNICATION AND COMMITMENT*

ALA AVOYAN[†] AND JOÃO RAMOS[‡]

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Abstract

We experimentally examine the efficacy of a novel pre-play institution introduced by [Calcagno et al. \(2014\)](#) in a well-known coordination game—the minimum-effort game—in which coordination failures are robust and persistent. This new institution allows agents to communicate while incrementally committing to their words, leading to a distinct theoretical prediction: the efficient outcome is uniquely selected in the extended coordination game. Commitment-enhanced communication significantly increases subjects’ payoffs and achieves efficiency levels considerably higher than non-binding communication considered in the paper. We document which aspects of the mechanism are critical for its success and the features of the environment to which the outcomes are invariant.

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[†]Department of Economics, Indiana University. E-mail: aavoyan@iu.edu

[‡]Department of Finance and Business Economics, Marshall School of Business, University of Southern California. E-mail: Joao.Ramos@marshall.usc.edu

1 Introduction

Economic situations often require agents to coordinate their actions, and coordination failures leading to underperformance are pervasive in society. Players face strategic trade-offs in coordination environments; in particular, to achieve better outcomes, they must choose an action that they are typically unwilling to take unless other players do the same. Although players in these environments desire the same outcome, strategic uncertainty leads to coordination failures. The literature seeking to identify institutions to overcome coordination failures uses controlled experimental environments to compare interactions under different institutions.

Given that players' interests are aligned in coordination games and that failure is rooted in uncertainty, institutions formalizing communication have been a natural starting point for attempted solutions to coordination failure. However, experimental evidence on the effects of communication is mixed, and communication alone may not be enough to ensure success, even in a controlled experimental setting.¹ Additionally, many of the studied pre-play interactions lack theoretical implications; therefore, even if a given intervention empirically improves coordination in the laboratory, it is unclear how to isolate the features underlying its success.

In this paper, we experimentally examine a novel institution studied theoretically by [Calcagno et al. \(2014\)](#)—asynchronous revision pre-play—which predicts that the Pareto-efficient profile is the unique outcome of an extended coordination game. In addition to the unique outcome prediction, the theory is used to obtain testable predictions of agents' dynamic behavior throughout the pre-play phase. The institution in [Calcagno et al. \(2014\)](#) formalizes the simple intuition that agents must prepare the actions that they intend to take at a predetermined deadline, and these preparations are public. As the deadline approaches, each player receives opportunities to update their prepared action at asynchronous and stochastically determined times. Once the players reach the deadline, their most recently prepared actions are implemented, and players' payoffs are determined by these actions only.

¹ Some communication protocols, such as two-way communication or public announcements, have been documented to increase coordination (see, e.g., [Cooper et al. \(1992\)](#), [Chaudhuri et al. \(2009\)](#), [Charness \(2000\)](#), [Blume and Ortmann \(2007\)](#), and [Burton and Sefton \(2004\)](#)). However, other protocols, such as one-way communication or private advice, have led to coordination failures (see [Cooper et al. \(1992\)](#), and [Chaudhuri et al. \(2009\)](#)).

In the laboratory setting, we embed the mechanism into a minimum-effort game, in which a player’s payoff depends on their own effort choice and the minimum effort chosen by the members of their group. We focus on this game because it is a prominent example of a coordination game with multiple Pareto-ranked equilibria. Moreover, a vast experimental literature observes coordination failures in this environment. To bring this institution to the laboratory, we extend its theoretical results, highlighting that some of the original assumptions are not essential for the main findings to hold, and we introduce discrete instead of continuous-time pre-play phase. Furthermore, we numerically solve the game for the specific payoff structure and parameters used in the experiment, which leads to an interesting prediction: subjects’ initial choices should be the efficient effort.

In the main treatment, *revision mechanism* (RM), the pre-play phase starts with all group members choosing an initial effort. If an opportunity arises, they can update this effort during a preparation phase of 60 seconds. Revision opportunities are awarded randomly to each group member, and the probability of two group members revising in the same instant is zero. In a single dynamic graph, each player can see real-time information on all group members’ posted effort choices, including the history of posted efforts, revision opportunities, and updates. Players can change their effort on their screen at any time (i.e., change their intention). Still, these revisions will not be publicly posted on the graph unless the player is awarded a revision opportunity. Throughout the 60-second preparation phase, each player is expected to receive eight revision opportunities. At the end of the pre-play phase, the players’ most recently revised efforts are implemented.

In this paper, we test whether a previously untested mechanism—asynchronous revision pre-play—can reduce coordination failures and allow the individuals involved to reach higher payoffs. Focusing on the efficiency gains, our first main result is, thus, that the mechanism increases efficiency by more than 65% compared with an environment without pre-play communication. The efficiency gains achieved with the revision mechanism (efficiency is 82%) are significant not only in comparison with the Baseline (48%) but also with the standard in the literature, one round of public cheap-talk messages (64%). Furthermore, we show that this efficiency gain follows from a combination of subjects choosing higher effort and subjects better coordinating on a particular effort profile (Result 1).

Going beyond the efficiency gains, we test two exact predictions of the theory. First, we examine whether this novel mechanism entirely eliminates coordination failures leading to

100% efficiency. Second, we examine whether 100% of subjects' initial choices are the efficient effort from the beginning. We show that efficiency in the revision mechanism treatment (82%) and the frequency of players choosing the efficient effort from the start of the pre-play (86%) are significantly different from the prediction of 100% (Result 2). Given the specificity of the unique outcome prediction and the simplicity of the equilibrium concept in the theoretical framework, some distance between the point predictions and subjects' behavior would be expected.²

To further understand how the revision mechanism affects behavior and, in particular, to determine whether such effect can be attributed to the forces behind the theoretical results, we concentrate on additional theoretical predictions. We study 6 additional insights from the theory, and we construct treatments to evaluate the empirical support for each one. Taken together, the empirical evidence indicates that subjects' behavior in the lab is mainly aligned with the theoretical forces, although significantly different from its point predictions. Let us look at each one of the insights separately.

We begin by investigating the robustness of the efficiency gain provided by the revision mechanism. The theory postulates that the same outcome should be observed independent of the initial effort profile. To test this, we consider a treatment called *random-revision mechanism* (R-RM), which is similar to the revision mechanism, except that subjects' initial choices are assigned to them at random. The theory also postulates that subjects' behavior should be the same for various payoff parameters. To test this prediction, we implement a treatment called *revision mechanism VHBB*, which is identical to the revision mechanism, except we use the main payoff parameters from [Van Huyck et al. \(1990\)](#). We show that subjects' performance in the revision mechanism is invariant to having exogenous initial choices and to a different set of payoff parameters (Result 3).

We then examine two assumptions that are key to the theoretical results. The unique outcome prediction relies on revision opportunities being frequent and asynchronous. First, to examine the role of revision frequency, we introduce *infrequent revision mechanism* (I-RM) treatment. In this treatment, the frequency of revisions is reduced to one-eighth of the frequency in RM. Second, to test the importance of asynchronicity, we introduce *synchronous revision mechanism treatment* (S-RM). In this treatment, when a group receives a revision,

² We further evaluate exact theoretical predictions of other treatments and papers in the literature in Appendix D.

every member in the group receives a revision opportunity at the same instance. We find that I-RM and S-RM lead to significantly lower efficiency levels than RM; hence, we conclude that the frequency and asynchronicity of revisions are empirically relevant for the success of the mechanism (Result 4).

Intuitively, the preparation phase allows players to communicate their intentions while incrementally committing to them. Formally, the action that a player chooses at any point in time may become their final choice, with some strictly positive probability. For the theoretical results, it is critical that players do not treat their preparations or others' prepared actions as cheap talk. To test this, we introduce *revision cheap talk* (R-CT) treatment. R-CT follows RM's protocol with one exception; when the 60-second pre-play is over, the subjects in R-CT can choose any effort they wish, and they are in no way committed to what they stated during the pre-play. Comparing the performance of the R-CT treatment with RM highlights the importance of commitment. While R-CT reaches 67% efficiency, RM reaches 82%. Therefore, the commitment in the revision mechanism is a relevant factor for the success of the mechanism (Result 5).

The last theoretical insight we examine is related to players' dynamic behavior. The player's best response depends not only on the effort profile chosen by others but also on time left before the deadline. If the time before the deadline is short, then a player should revise her effort to be the minimum of the group—maximizing her payoff. In contrast, if the time is large enough, the proposition dictates that it is optimal for a player to revise their effort upward and initiate a chain reaction that will end with all players choosing the efficient effort. We find that in R-RM, early revisions are vastly forward-thinking, while late revisions are myopically payoff-improving.

Finally, we investigate how subjects communicate in different treatments. We are interested in how communication and commitment interact to improve coordination in the revision mechanism. We show that commitment affects what is communicated by players and makes the communication more credible (Result 7). Further, we show substantial differences between what subjects say and do in the absence of commitment, even with multiple rounds of communication (Result 8). Moreover, we find similar results even if we expand the message space to include what subjects think others should do. Enriching the communication to include explicitly labeled messages about group behavior does not significantly improve subjects' payoffs, further highlighting the importance of commitment (Result 9).

The institution experimentally studied in this paper is predicated on the combination of three key ingredients: a setting in which players would like to coordinate their actions; a pre-play phase during which players publicly state their intended actions; and incremental commitment, as preparations cannot be changed instantaneously. Given this, the revision mechanism experimentally studied in this paper can be interpreted in two distinct ways. First, the revision mechanism can represent an intentionally designed institution for implementing the efficient outcome. In this sense, the experiment has practical implications for the designer. We illuminate the assumptions and forces relevant for the success of this complex theoretical mechanism, which is instrumental for the proper design of a mechanism adapted to a particular real-world setting. Second, the mechanism can be understood as a realistic model of some real-world coordination. Although not always formal, scenarios in which preparation, communication, and incremental commitment go hand-in-hand form an integral part of our social lives.

Let us consider two examples in the real world that mimic the mechanism studied in the paper. First, consider a group of friends organizing a night out. One might assume that the more friends that show up, the more enjoyable it will be. Also, friends communicate their plans before the date. Finally, although no explicit commitment or enforceable contract exists, social norms dictate that going back on one's word is costly. Effectively, bailing out on your friends might be too socially costly, mimicking commitment. However, an unrelated random event (e.g., an urgent task at work, a sick kid, a stomach ache, a friends' break-up) might offer an opportunity to revise one's commitments with no consequences.

Second, consider a joint military operation. Many different parties need to coordinate their actions for the operation to be successful. Furthermore, the parties prepare and train for the operation, with each battalion, branch, and country allocating a certain pool of resources to the joint operation. While there might not be any formal commitment over these promised resources, the cost of not delivering the agreed manpower without justification can be immense. However, given limited supplies, especially during warfare, events out of control of the parties—for instance, casualties, bombings, and changes in military configuration—might give the party a chance to re-optimize the allocation of resources, effectively revising previous commitments.³

³ Following the 9/11 attacks, France quickly expressed its support to the United States and joined the war effort in Afghanistan, citing the importance of NATO commitments. French president Sarkozy increased the

2 Literature Review

A large experimental literature, spurred by [Van Huyck et al. \(1990\)](#), has established that coordination failures—ubiquitous in the real world⁴—are also common in experimental settings. The main contribution of our paper is the examination of how commitment enhanced pre-play communication can help reduce coordination failures and improve subjects' payoffs. In addition, given the mechanism studied in this paper, our results relate to the literature that focuses on the effects of commitment and real-time interaction on coordination.

In coordination environments, players face a very particular trade-off because their preferences are more aligned with those of others than in most other strategic situations. The main hurdle for coordination and efficiency is the presence of strategic uncertainty. Some researchers argue that costless pre-play communication could eliminate this hurdle. [Blume and Ortmann \(2007\)](#) and [Deck and Nikiforakis \(2012\)](#) implement a cheap-talk communication phase before the actual play in a minimum-effort game. The pre-play communication in [Blume and Ortmann \(2007\)](#) is done with one round of simultaneous public messages, whereas the protocol in [Deck and Nikiforakis \(2012\)](#) allows for richer interaction, with the subjects having one minute to choose an effort level and being able to revise their chosen effort at any time. Cheap-talk communication improves coordination and boosts efficiency to 69% and 71% (from 34% and 44%)⁵ in [Blume and Ortmann \(2007\)](#) and [Deck and Nikiforakis \(2012\)](#), respectively. Despite the ability to update the messages at any second in [Deck and Nikiforakis \(2012\)](#), the efficiency levels in these papers are similar, suggesting that multiple rounds of cheap-talk communication do little to improve efficiency over a single round. Moreover, the gains from the baseline are higher in [Blume and Ortmann \(2007\)](#) than in [Deck](#)

war effort in 2008, sending more troops and resources even after ten French soldiers were killed in 2008. As the popularity of the war declined, the French president changed posture and pressured for a quick withdrawal of troops. In January 2012, after an Afghan soldier shot and killed four French soldiers in eastern Afghanistan, French President Nicolas Sarkozy decided to unilaterally speed up the withdrawal of French operations in Afghanistan, ahead of NATO schedule.

⁴ For instance, see [Rosenstein-Rodan \(1943\)](#), [Murphy et al. \(1989\)](#), [Matsuyama \(1991\)](#), [Rodrik \(1996\)](#), and [Li \(2012\)](#).

⁵ We use normalized efficiency throughout this paper as it summarizes the strength of the treatments. Also, normalized efficiency allows us to compare results from frameworks with different payoffs or group sizes. In particular, our paper, [Blume and Ortmann \(2007\)](#), and [Deck and Nikiforakis \(2012\)](#) each use a different payoff specification. Group size in the current paper is the same as in [Deck and Nikiforakis \(2012\)](#) but is different than in [Blume and Ortmann \(2007\)](#). We provide more details of the measure in the results section.

and Nikiforakis (2012). Similarly, in this paper, we find that cheap-talk treatments produce similar efficiency levels regardless of whether pre-play communication consists of simultaneous one-shot public messages, multi-round rich communication, or a richer message space.

The communication studied in this paper contains no explicit cost of sending messages. However, there is an implicit cost of communication—the inability to revise the intended effort choices instantly. Van Huyck et al. (1993) and Devetag (2005) consider a costly form of pre-play communication (a pre-play auction in each round) and conclude that such an extension enables the players to achieve better coordination on the payoff-dominant profile in coordination games. Kriss et al. (2016) study the effects of costly and voluntary communication with full and partial subsidies on coordination in a minimum-effort game. The authors find that even a small cost of message sending deters subjects from communication and leads to high coordination failures. Fehr (2017) endogenizes the presence of pre-play communication in an environment in which two groups with prior coordination history are merged. The author finds that most subjects are unwilling to pay a small cost of establishing and maintaining pre-play communication.

To our knowledge, our paper is the first to experimentally study the effects of incremental commitment in a coordination game. The impact of incremental commitment on cooperation has been studied in the context of public goods games. Building on insights by Schelling (1960), Dorsey (1992) is the first to introduce revisions and real-time monitoring in a voluntary contributions mechanism. Looking at those results from a different perspective, Duffy et al. (2007) test theoretical predictions about the dynamic voluntary-contribution game in Marx and Matthews (2000) and show that, whereas a dynamic setting increases the rate of contributions compared with a static setting, the results do not seem to be driven by the theoretically identified forces. Fundamental differences exist between the forces that impede coordination on the Pareto-efficient equilibrium in coordination games and the forces that drive the lack of cooperation in the public-goods provision and social dilemmas. In the latter, the trade-off is between efficiency and individual rationality. In contrast, in coordination games, the miscoordination is a result of the multiplicity of equilibria along with a lack of selection criteria, leading to strategic uncertainty. Contrasting our results with those of Duffy et al. (2007) highlights how different the two settings are. In this paper, we show that pre-play revisions significantly improve efficiency in coordination games, and we are also able

to highlight the critical assumptions for its success.

Roy (2017) experimentally studies the market competitiveness in a Cournot duopoly in which firms can simultaneously revise their targeted quantities before the final production. Building on the revision-games theoretical results in Kamada and Kandori (2017), Roy (2017) tests the prediction that a synchronous revision Cournot duopoly may result in higher collusion than in the case without stochastic interaction. Although the theories that predict more collusion in Roy (2017) and higher coordination in our paper have some overlap, the forces behind them are fundamentally different. First, when a revision phase is introduced to a Cournot duopoly, the set of possible equilibrium outcomes increases, and collusion becomes theoretically sustainable. By contrast, the introduction of a revision phase to coordination games shrinks the set of equilibrium-supported outcomes to the unique Pareto-efficient profile. In addition, the revision phase studied theoretically in Kamada and Kandori (2017) and experimentally in Roy (2017) has synchronous revision opportunities. In contrast, for the theory developed in Calcagno et al. (2014) asynchronicity is key to mitigate strategic uncertainty in coordination games. Aligned with that, we show the empirical relevance of asynchronicity (see Section 5.3.2). Inefficiencies in coordination settings and the Cournot duopoly arise from fundamentally different forces, calling for different mitigation mechanisms. In coordination settings, we show that introducing incremental commitment leads to credible communication that will effectively help agents coordinate on a Pareto-dominant outcome.

3 General Framework

3.1 Component Game

Consider a normal-form game $(I, (E)_{i \in I}, (\pi_i)_{i \in I})$, where I is a finite set of players, $I = \{1, 2, \dots, n\}$; E is a finite set of effort levels available to each player i ; and $\pi_i(\mathbf{e})$ is the payoff for player i given the strategy profile $\mathbf{e} \in \mathbf{E}$, where $\mathbf{e} = (e_i)_{i \in I}$ and $\mathbf{E} = \prod_{i \in I} E$.

The results presented in Calcagno et al. (2014) and the results discussed here hold for a wide class of games with common interest.⁶ In our experiments, we focus on a particular

⁶ A game is a common-interest game if it has a strictly Pareto-dominant action profile.

payoff structure, the minimum-effort game, with payoffs given by

$$\pi_i(\mathbf{e}) = \gamma + \alpha \cdot \min_{j \in I} e_j - \beta \cdot e_i, \quad (1)$$

where $\alpha > \beta > 0$. A player's payoff decreases with higher choice of effort and increases with the minimum effort among all the players. This is a game of common interest, as the strategy profile $\bar{\mathbf{e}}$ strictly Pareto dominates any other profile. Let $\underline{\pi}_i(\underline{e})$ be the worst possible payoff for player i , reached when i chooses \bar{e} and at least one player in their group plays \underline{e} .

Equilibrium analysis of the minimum-effort game: The minimum-effort game described above has multiple pure-strategy Pareto-ranked Nash equilibria. Every profile in which all players choose the same pure strategy is a strict Nash equilibrium. These equilibria can be Pareto ranked by the effort choice: the higher the effort, the more efficient the equilibrium. In particular, let \bar{e} be the highest element of E and let \underline{e} be the lowest; then, $\pi_i(\bar{\mathbf{e}})$ is the highest equilibrium payoff for player i , whereas $\pi_i(\underline{\mathbf{e}})$ is the lowest possible equilibrium payoff, in which $\bar{\mathbf{e}}(\underline{e})$ denotes the profile for which all players choose $\bar{e}(\underline{e})$.

Before proceeding, we must introduce a definition that is key to the result from [Calcagno et al. \(2014\)](#) in a wide set of games.⁷ Below, we apply this definition to the minimum-effort game.

Definition 1 *Calcagno et al. (2014)*

A component game with common interest is a K -coordination game if, for any pair of players $i, j \in I$ and strategy profile $\mathbf{e} \in \mathbf{E}$,

$$\frac{\pi_i(\bar{\mathbf{e}}) - \pi_i(\mathbf{e})}{\pi_i(\bar{\mathbf{e}}) - \pi_i(\underline{\mathbf{e}})} \leq K \frac{\pi_j(\bar{\mathbf{e}}) - \pi_j(\mathbf{e})}{\pi_j(\bar{\mathbf{e}}) - \pi_j(\underline{\mathbf{e}})}. \quad (2)$$

A game is a K -coordination game if each player can decrease other players' payoffs by at most K times their own cost of punishment. The constant K captures how similar the players' payoffs are between different action profiles. Applying this to the minimum-effort game, if a player choosing the minimum effort reduces their effort choice by one unit, then their own payoff decreases by $\alpha - \beta$, while other players' payoffs decrease by α . In a general game, the smaller K is, the more similar players' preferences are. In particular, if $K = 1$,

⁷ See [Takahashi \(2005\)](#) for the definition and discussion of the concept.

the game is a pure coordination game, and players have identical payoffs for any outcome. Any finite game with common interest is a K -coordination game for some finite constant $K \geq 1$. Finally, given the payoff structure of the minimum-effort game, the definition can be further simplified: a component game is a K -coordination game if $\frac{\alpha}{\alpha-\beta} \leq K$.

3.2 Pre-play Communication

Theoretical work regarding cheap-talk pre-play communication in coordination games has focused on evaluating the credibility of a message profile. The idea is that pre-play communication will promote Pareto-efficient Nash equilibrium play if players' messages are credible when they communicate their intentions to take a certain action. The literature has proposed several requirements for a message to be considered credible.

The early literature considers one-way communication and analyzes the credibility of a message in isolation. For instance, [Farrell \(1988\)](#) postulates that a message is credible if it is self-committing: if the message is to be believed, a sender's best response is to follow the intention stated in the message. If we consider the minimum-effort game with one player sending a public message to all other players, then sending an efficient-effort message is self-committing. If all receivers believe the message and choose the efficient effort, the sender's optimal choice is to follow the message and choose the efficient effort as well. [Aumann \(1990\)](#) challenges the above reasoning, focusing on whether the sender has a strict preference over the other players' strategy choices. The author argues that, when the sender wants the receiver to believe the message, whether or not they intend to act in accordance with it, the message has no credibility. For [Aumann \(1990\)](#), a message leads to effective communication only if it is self-signaling: the sender wants their message to be believed if, and only if, they plan to follow the intention conveyed in the message. Note that, in the minimum-effort game, a player weakly prefers that other players choose the efficient effort level, independent of the player's choice; hence, messages signaling the intent to choose efficient effort are not self-signaling.

Self-committing and self-signaling are both concepts that relate to individual messages. Although the definitions could be intuitively generalized to the case of multilateral communication, message credibility needs to be defined for profiles of messages, not for individual messages. A player can simultaneously be a sender and a receiver of a message, and a player might send a message linked to one equilibrium and receive a message linked to another.

In particular, [Blume \(1998\)](#) argues that communication makes an equilibrium profile more attractive for a player only if all players communicate homogeneously, agreeing on the equilibrium in question.⁸ In a minimum-effort game with one-shot multilateral communication, if the chosen message profile is homogeneous, then the associated equilibrium profile could be considered more salient. However, no consensus exists on how to interpret heterogeneous message profiles, and the standard prediction is that communication will be ignored.

3.3 Asynchronous Revision Game

Consider an environment in which players must prepare their actions before they execute them. We follow [Calcagno et al. \(2014\)](#) in modeling this as an asynchronous revision game: there is a pre-play phase, during which a player can revise their prepared action only if a revision opportunity is awarded to them. At the end of the pre-play phase, the most recently prepared action profile is played and players collect the payoff associated with that action profile. While [Calcagno et al. \(2014\)](#) model an asynchronous revision game with a continuous-time pre-play phase and revisions governed by independent Poisson processes, we extend their results to an environment with discrete time and multinomial revisions.

Formally, we model this as an asynchronous revision game with discrete time, $t \in \{-T, \dots, -1, 0\}$. The game proceeds as follows. First, at time $-T$, an initial effort profile is in place. It can be exogenously given to the players, or each player can simultaneously and independently choose an effort level before the pre-play starts. Second, during the pre-play phase, $t < 0$, each player obtains revision opportunities according to a random process with a symmetric arrival rate. At each instant, a revision opportunity is awarded to the group with probability $p \in (0, 1]$. If a revision opportunity is awarded to the group, then it is allocated to one of the players with equal probability. Third, at the end of the countdown, $t = 0$, the posted effort profile is implemented, and each player receives the payoff as specified in the component game.

This is a sequential game with multiple rounds of asynchronous play and perfect infor-

⁸ The results in [Blume \(1998\)](#) are achieved with costless messages and the additional assumption of messages having some a priori informational content. [Hurkens \(1996\)](#) first obtained similar results with costly messages and no additional assumptions on messages. Moreover, the result extends to two-sided communication if there are only two players, and the underlying game is common interest (see, also, [Sobel \(2017\)](#), where iterated weak dominance can select the Pareto-efficient outcome with one-sided pre-play communication in two-player games). However, the results fail even with common-interest coordination games when there are three or more players.

mation, as players observe all the past events in the revision game. The natural solution concept is subgame perfect equilibrium. We refer to a subgame perfect equilibrium of a revision game as *revision equilibrium*. Below, we present the main theoretical result, which is an extension of the result in [Calcagno et al. \(2014\)](#) to the framework presented above. The proof is presented in [Appendix A](#).

Proposition 1 *In a discrete-time asynchronous revision game with a symmetric arrival rate of revision opportunities, if the component game is a K -coordination game with the strict Pareto-dominant action profile, \bar{e} , and the game satisfies $(n - 2)K < (n - 1)$, then for any $\varepsilon > 0$, there exists $T' > 0$ such that for all $T > T'$, all revision equilibria have $e(\mathbf{0}) = \bar{e}$ with probability higher than $1 - \varepsilon$.*

According to [Proposition 1](#), in any revision equilibrium of a long enough revision game, all the players choose the efficient effort in the payoff-relevant moment with probability close to one. Interestingly, this result holds independent of the effort configuration at the beginning of the revision phase. If the time horizon is long enough, then at $t = 0$, all players will be choosing the efficient effort (with probability $1 - \varepsilon$). That is, even if all players start with the minimum effort, or if it is randomly determined, or if players choose simultaneously at $-T$, all players will be choosing the efficient-effort at $t = 0$ with probability at least $1 - \varepsilon$. It is essential to highlight that, if the conditions for the proposition fail—for instance, if the pre-play phase is too short—then [Proposition 1](#) does not indicate anything about equilibrium selection. In particular, the efficient effort profile, \bar{e} , would still be one possible effort profile played at the end of the pre-play in an equilibrium of the game, but it would not be the unique outcome of a revision equilibrium. A different equilibrium could have all players preparing the lowest effort at the end of the pre-play.

In [Appendix B](#) we go beyond the proposition and, given the parameters used in the experiment, we numerically solve the game by backward induction. We consequently gain two additional insights into the revision equilibrium strategy. First, if players can choose their effort before the pre-play, then the revision equilibrium prescribes that all choose the efficient effort from the start. Second, if a player has a revision opportunity far enough from the deadline, then it is optimal to revise to the efficient effort, irrespective of what other players are preparing. Solving the game by backward induction also allows us to go beyond the proposition. We show that, for the minimum-effort game, the condition stated in the

Proposition 1 is sufficient, but not necessary.⁹ In Appendix B, we show that, for different payoff specifications (even specifications that do not satisfy the condition in Proposition 1), if the pre-play phase is long enough, then the efficient effort profile, \bar{e} , is selected as the unique outcome of a revision equilibrium.

Next, we discuss the argument of the proof. The proof closely follows the steps from Calcagno et al. (2014) and is presented in Appendix A. Intuitively, the proof can be divided in two parts. The first part shows that, if all players are choosing the highest effort at a time t , then there is a unique subgame-perfect equilibrium payoff, $\pi(\bar{e})$. That is, the Pareto-dominant equilibrium profile, \bar{e} , is absorbing: if a subgame starts with the efficient effort profile, \bar{e} , then the unique subgame-perfect equilibrium in that subgame has all players preparing the maximum effort along the equilibrium path.

The second step of the proof begins by constructing a lower bound for the payoff of a player who chooses the highest effort well before the deadline. The main step of the proof is to show that, in any subgame perfect equilibrium, if there is enough time before the deadline, then—independently of how many players are choosing the efficient effort at a time—such a bound converges to the efficient payoff. This is done by induction on the number of players choosing the highest effort, \bar{e} , at a time t far enough from the deadline. The revision frequency condition stated in the proposition is sufficient to guarantee that the time needed for the induction step is finite. Thus, when far from the deadline, independent of the current effort choices, by selecting the highest effort, a player is guaranteed a payoff close to the efficient payoff with probability close to one.

3.4 Exact predictions and qualitative insights

Before we describe the experimental design of the paper, we must distinguish between *the exact theoretical predictions* and *the qualitative insights* laid down by the forces behind such results. Two specific predictions arise from the theoretical setup. First, players' payoff should be close enough to the efficient payoff. Second, in terms of players' choices, when enough time remains before the deadline, it is optimal to revise the effort choice to the efficient effort at the first revision opportunity awarded (see Appendix B). Furthermore, this

⁹ In Calcagno et al. (2014), the authors show that the condition is tight for the general case. That is, for any $K > 1$, it is possible to find a K -coordination game such that the condition is necessary and sufficient for the proposition. In this paper, we focus on a particular game: the minimum-effort game.

implies that, if players can choose their initial effort, all players should choose the efficient effort from the start.

Going beyond these specific predictions, there are six general insights generated by the theoretical forces at play in this framework. Analyzing these general insights could yield a better understanding of how this institution affects players' behavior. The first two insights focus on the robustness of the equilibrium selection result. First, the theory suggest one should expect the same outcome irrespective of whether the initial choices are chosen by the players or picked at random before the pre-play starts. Second, the theory proposes that the same outcome should be expected for different payoff specifications (within some parametric limits).

The third and fourth insights consider the central elements that allow for the backward induction argument to select a unique outcome of any revision equilibrium in the proof of Proposition 1. The third insight is that, as explicitly stated in Proposition 1 and verified numerically in Appendix B, the selection of a unique revision equilibrium is conditional on the presence of frequent enough revision opportunities. If revisions are infrequent or if the pre-play phase is too short, then the uniqueness result is not obtained, and all the equilibria of the component game are the outcome of a revision equilibrium of the extended game.

The fourth qualitative insight highlights the importance of revisions being asynchronous for the backward induction argument behind the proof of Proposition 1. A player's ability to influence other players' subsequent choices is key for the result, and it relies on the existence of proper subgames in the revision game. If a player cannot condition her behavior on the effort choices of other players, such as when all players have synchronous revisions, then the revision phase has no proper subgame. In that case, the repetition of any static Nash equilibrium is a revision equilibrium of the extended game.

Finally, the last two qualitative insights extend further into the structure of the proof of Proposition 1. The fifth insight is that, although players can use revisions to communicate with other players, a revision is not cheap-talk communication. Although revisions are frequent, there is still a positive chance of not having any revision in the future. Furthermore, for a fixed frequency of revisions, as time passes in the pre-play phase, players further commit to their prepared actions incrementally because the chance of not having a revision increases. In the proof of Proposition 1, it is key that players do not treat their own preparations, or others' prepared actions, as cheap talk.

The last (sixth) qualitative insight postulates that a player’s best response to a revision opportunity (given the effort profile being prepared) depends on the time left before the deadline. The proof of Proposition 1 and the numerical exercise in Appendix B rely on that. For instance, consider that, at a time $-t$, all players are choosing the minimum effort, and player i has a revision opportunity. If t is small, it is clear that it is optimal for player i to revise their effort choice to their myopic best response—the minimum effort. Any other choice of effort would yield higher payoffs only if all other players revised their choices. With t being small enough, the probability of no revisions grows large. In contrast, if t is large enough, the proposition dictates that it is optimal for player i to choose in a forward-thinking way, to revise their effort upward, and to initiate a chain reaction that will end with all players choosing the highest effort. In Appendix B, we provide more details on how the best response is affected by the amount of time remaining before the deadline, given our payoff parameters in the experiment.

4 Experimental Design

In this section, we first present three main treatments that establish the effect of the revision mechanism. Then we describe additional treatments to test the exact prediction and theoretical insights discussed in Section 3.4.

The experimental sessions were conducted at the Center for Experimental Social Science (CESS) laboratory at New York University (NYU) and at the Interdisciplinary Experimental Laboratory (IELAB) at Indiana University (IU), using the software z-Tree (Fischbacher (2007)). All participants were NYU or IU students. The experiment lasted about 45 minutes, and subjects earned, on average, \$18, which included the \$8 show-up fee. In each session, written instructions were distributed to the subjects and also read aloud.¹⁰

In all treatments, participants were randomly divided into groups of six, and they participated in a sequence of 10 rounds as a part of that group.¹¹ In each round, the group played the minimum-effort game with effort choices from 1 to 7 ($E = \{1, 2, 3, 4, 5, 6, 7\}$). For all but one treatment, the subjects have the same payoff function: $\pi_i(e) = 0.18 - 0.04 \cdot e_i + 0.2 \times \min_{j \in I} e_j$. For treatment revision mechanism VHBB (RM-VHBB), the payoff func-

¹⁰ Instructions used in our experiment can be found in the Online Appendix.

¹¹ At IU, each session included only one group with six subjects. At NYU, a session included either 12 or 18 subjects.

tion is $\pi_i(e) = 0.60 - 0.1 \cdot e_i + 0.2 \times \min_{j \in I} e_j$, as the primary parameters in [Van Huyck et al. \(1990\)](#). The payoffs were described to subjects in matrix form, and the subjects took a comprehension test to ensure that they understood the payoff structure. After 10 rounds, subjects answered a short survey and were paid their final payoff, which was the sum of the payoffs from all 10 rounds plus the show-up fee (survey results are summarized in [Appendix C](#)).

4.1 Baseline

The baseline treatment replicates the standard control treatment in the literature. Subjects play the normal-form one-shot game. After each round of playing a standard simultaneous minimum-effort game, participants receive feedback on the minimum number chosen in their group in that round. This information is the only history available to them in the baseline treatment.

4.2 Revision Mechanism (RM)

We design a treatment that closely replicates the conditions of our theoretical setup to test the power of the pre-play revision mechanism in aiding coordination. Implementing this institution in the laboratory presents several challenges.

One challenge is that the game involves frequent interaction among players, and they need to have all the information at every period. Thus, each player's revision opportunity and posted effort, as well as the history of posted efforts and revisions, should be available to all players at all times. We compile this information in a graph that summarizes all the key points and represents the players' efforts in different colors. Every time a player receives a revision opportunity, a dot appears on that player's action line. The graph summarizes all the key information and makes it easily accessible to the subjects.

Another challenge is implementation of revision opportunities. Theory dictates that revisions should happen frequently. If we stop ("freeze") the phase every time a subject receives a revision opportunity, the phase could last a long time. To control how long a phase lasts, we let subjects change a number any time they want; all they need to do is place the cursor over the button on the screen. However, the subject's new selection is updated on the graph only after the subject receives a revision opportunity. A byproduct of this method is that we gather two streams of data, payoff-relevant decisions and what subjects want to do (we use

this data to test the choice of certain parameters in our experiment, see Appendix F).¹²

In the RM treatment, each round begins with all members of the group simultaneously choosing a number from 1 to 7.¹³ Once all group members make their initial choices, a graph¹⁴ appears, and a one-minute countdown begins. In Figure 1, we present an example of the graph after 30 seconds of the countdown. The time in seconds is on the horizontal axis, and the number chosen by each of the group members is on the vertical axis. The initially chosen numbers are along the vertical line above the zero-second mark. Each player is represented on the graph by a different color. As the countdown progressed, at any time, any member of the group can change their chosen number by placing the cursor on the desired number on the left side of the screen. When a subject selects a number, the respective button turns green (see the number 4 in Figure 1). The number posted on the graph only updates when the subject receives a revision opportunity.

On average, a subject receives eight revision opportunities in one round. Formally, at every second, the group has an 80% chance of receiving a revision opportunity; if that occurs, then the six group members have an equal probability of 1/6 of receiving the revision opportunity.¹⁵ Only the numbers posted at the end of the countdown matter for the payoff. The initially chosen efforts and all the revision effort choices are irrelevant for payoff.

Consider the actions of player Green (thicker line on the graph), whose screen is in Figure 1. Along the vertical line above the zero-second mark, we see a green dot in interval 2, which means that Green's initial choice was 2. A dot on the green line (thicker line) at the five-second mark indicates that Green received a revision opportunity; however, because the effort after that was not updated, Green had not changed the intended effort, still choosing 2. At the 15-second mark, we see a shift of the green line from the effort-2 interval to the effort-

¹² We thank Bigoni et al. (2015) and Friedman and Oprea (2012) for sharing their code with us.

¹³ Data for RM were collected both at NYU and IU. Data for eight groups were gathered at NYU and for eight groups at IU, resulting in 16 groups for this treatment. We do not find any considerable differences between the two locations, and we therefore combine the data for the analysis throughout the paper.

¹⁴ We explained the graph in great detail in the instructions, and all subjects took a comprehension test regarding the graph and payoff table.

¹⁵ The theoretical result in Proposition 1 requires the revision opportunities to be frequent enough or the length of a round to be long enough (these two parameters are interchangeable). In Appendix B, we numerically compute the time horizon needed for our results to hold, given 0.8 probability of revision frequency used in RM treatment the horizon is calculated to be about 12 seconds. Furthermore, in Appendix F, we use the data to test whether the parameters T and λ in the RM treatment bind players' choices, and we conclude the specifications were not binding.



Figure 1: Sample Screen after 30 Seconds in RM

6 interval. This shift implies that in the 15th second, Green received the revision opportunity, before which they switched their effort from 2 to 6. At about the 25-second mark, the green dot on the line reveals an unused revision opportunity, as the green line is still in interval 6. On the left side of the graph in Figure 1, the number 4 is highlighted, which implies Green switched intended effort from 6 to 4. However, a revision opportunity has not yet occurred; thus, the posted effort on the graph for Green is still 6.

4.3 Standard cheap talk (S-CT)

The standard cheap-talk treatment offers subjects multilateral one-shot communication, similar to the main communication treatment in [Blume and Ortmann \(2007\)](#). In this treatment, before subjects make their payoff-relevant effort choices, they simultaneously send a public message (a number from 1 to 7). This is followed by 60 seconds during which subjects see all the messages sent by their group members (including their own message).¹⁶ After the subjects see the messages, buttons appear, and they make their payoff-relevant effort choices (all the group messages are visible on the screen when subjects make their payoff-relevant decision). At the end of the round, the subjects see a feedback page with their choice and the

¹⁶To ensure that subjects spend the same amount of time in the lab and have an experience similar to that of the RM treatment, we display the messages sent by subjects on a graph and give the subjects 60 seconds to make payoff-relevant effort choice.

minimum number chosen by the group.

4.4 Random Revision Mechanism (R-RM)

In random revision mechanism (R-RM), initial choices are randomly chosen for the subjects.¹⁷ However, the rest of the round is executed identically to the RM protocol. We know, theoretically, that the outcomes of this treatment should be similar to those of RM; however, we get a much richer best-response behavior due to the initial heterogeneity of effort choices.

4.5 Revision mechanism VHBB (RM-VHBB)

The revision mechanism VHBB treatment is identical to RM treatment, except for the payoff parameters. In RM-VHBB we use the main payoff parameters used in [Van Huyck et al. \(1990\)](#) ($\alpha = 0.2$, $\beta = 0.1$, and $\gamma = 0.6$).

4.6 Infrequent revision mechanism (I-RM)

In the infrequent revision mechanism, we reduce a group's probability of having a revision opportunity from 0.8 of RM to 0.1. In RM, the chance of having no more revisions 60 seconds before the deadline is approximately 0.01%, while in I-RM, it is 36%. In [Appendix B](#), we numerically solve the game with 0.1 as the probability of a revision opportunity, and we find that at least 164 seconds per round would be needed for the theoretical results to hold.

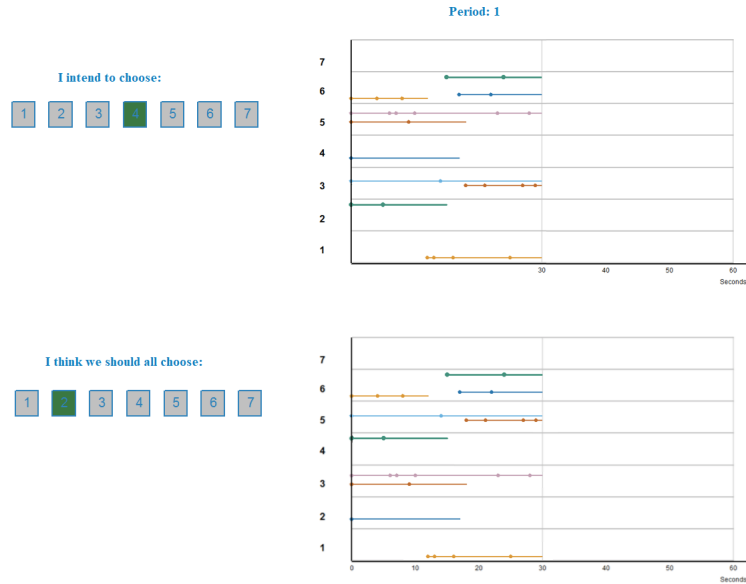
4.7 Synchronous revision mechanism (S-RM)

The synchronous revision mechanism is identical to RM, except the revisions for all subjects in a group occur at the same time. Recall, in RM, every second a revision is awarded to a group with 80% chance. When a revision opportunity is awarded to a group, it is given to one of the group members with equal probability. In contrast, in S-RM, when a group receives a revision opportunity, all group members receive it at once.¹⁸ Note that the expected number of revisions per subject in S-RM is eight revisions, the same as in RM. The only difference between RM and S-RM is that the revisions in S-RM are synchronous, while revisions in

¹⁷ The random process for the initial-choice assignment is uniform over all possible efforts, and all groups face the same initial effort distributions.

¹⁸ The realizations of revision opportunities used in S-RM are the same as the realizations of revisions in RM for one of the group members.

Figure 2: Sample Screen after 30 Seconds in R-R-CT



RM are asynchronous.

4.8 Revision cheap talk (R-CT)

The revision cheap talk treatment follows the RM pre-play phase protocol. First, all members of the group simultaneously chose an integer from 1 to 7; then, once everyone makes a choice, the one-minute countdown begins. As in the revision mechanism, all members of the group see the same real-time graph, and the effort chosen is updated only when a revision opportunity is awarded.¹⁹ In contrast to RM, the choice at the end of the countdown is not payoff-relevant in R-CT. Once the 60-second countdown is over, a new screen appears, and subjects chose an integer from 1 to 7 that determines their payoffs.²⁰

¹⁹ The revision realizations used in R-CT are the same as in RM.

²⁰ This treatment was conducted in two ways. For eight groups, while subjects were making payoff-relevant choices, the graph from the round was not present. To avoid concerns about memory issues, we re-run this treatment with an additional eight groups. For these subjects, when payoff-relevant buttons appeared, the graph with the history of 60 seconds was present on the same screen. Because we do not find any considerable differences between the groups, we combine the data and have 16 groups for R-CT treatment.

4.9 Richer revision cheap talk (R-R-CT)

In the richer revision cheap talk treatment, subjects can inform others what they intend to play as well as what they think everyone should play. R-R-CT has a protocol similar to R-CT, except that in R-R-CT, subjects observe two sets of buttons and two graphs. Figure 2 presents a sample screen presented to the subjects. After 60 seconds, the graphs stay on the screen and buttons appear, which subjects use to make payoff-relevant choices. After every group member has made their choice, subjects observe a feedback page presenting their choice and the minimum of their group.

Table 1 summarizes our experimental design and highlights the differences between our treatments based on the two main dimensions: communication and commitment.

Table 1: Experimental Design

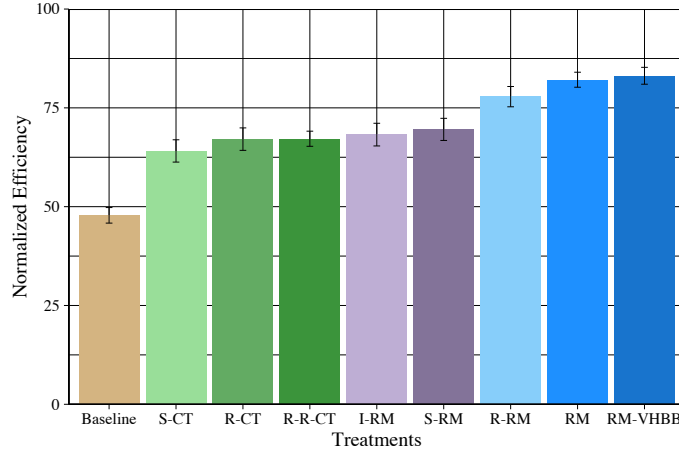
Treatment	Communication	Commitment	# Subjects
<i>Baseline</i> ²¹	None	NA	48
<i>Revision Mechanism (RM)</i>	Revisions	Gradual	96
<i>Standard Cheap-Talk (S-CT)</i>	One-shot	None	48
<i>Random RM (R-RM)</i>	Revisions	Gradual	48
<i>RM VHBB (RM-VHBB)</i>	Revisions	Gradual	48
<i>Infrequent RM (I-RM)</i>	Revisions	Abrupt	48
<i>Synchronous RM (S-RM)</i>	Revisions	Gradual	48
<i>Revision Cheap-Talk (R-CT)</i>	Revisions	None	96
<i>Richer R-CT (R-R-CT)</i>	Revisions	None	48

5 Results

In this section, we first establish the main result of the paper: introducing a revision mechanism to a minimum-effort game significantly improves efficiency compared with both the one-shot game and the one-shot game preceded by a round of one-shot cheap-talk communication (RM vs. Baseline and RM vs. S-CT). We then test the exact predictions of the theory highlighted in Section 3.3. We proceed by using additional treatments described in Section 4 to shed light on the six insights provided by the theory, discussed in Section 3.3. Finally, we take a deeper look into how subjects communicate and how commitment affects their

²¹ One session of the baseline treatment was voided because one of the subjects publicly announced an intended action and asked others to play the same. We ran an extra session to replace the voided session.

Figure 3: Treatment normalized efficiency



communication.²²

5.1 Overall effect of revision mechanism

We first focus on the overall efficiency of treatments. We follow the literature and calculate normalized efficiency as

$$Efficiency = \frac{Actual - Min}{Max - Min}, \quad (3)$$

where *Actual* is the average amount earned in a treatment, and *Min* (*Max*) is the average minimum (maximum) possible amount that a subject can earn. Results are displayed in Figure 3. The RM efficiency is 82.1%, whereas, in Baseline and S-CT treatments, the efficiency is 47.8% and 64.1%, respectively. The introduction of the revision mechanism restores more than half (65.7%) of the efficiency loss in the Baseline. This captures a substantive difference in payoffs, with subjects in RM earning, on average, 44% higher payoffs than in Baseline and 23% higher payoffs than in S-CT.²³

Given the payoff function for the minimum-effort game (see equation 1), deviations from the efficient equilibrium reduce payoffs in two ways. First, subjects choose an inefficient

²² For the most part of this section we focus on aggregate statistics and overall effects of the treatments. In Appendix E.5 we provide more details on variables of interest over 10 rounds and within 60 second pre-play phase.

²³ See Tables 5 and 6 in Appendix E.2 for details on average payoffs and other relevant variables as well as the statistical test results between the revision mechanism and other treatments.

minimum effort and, second, subjects miscoordinate and select different efforts. We now focus on outcome variables to capture the effect of RM over these two forces and compare it with other treatments. To capture if subjects try to coordinate on the efficient profile, we analyze the minimum effort of the group as well as the frequency of efficient effort choices. To assess the coordination on any effort profile achieved by the group, we rely on the fraction of fully coordinated groups and a novel measure, *equilibrium deviation*, which captures how far a group is from full coordination. Equilibrium deviation calculates, for each group, the average distance between the effort choices and the myopic best response—the minimum effort chosen in the group. Note that equilibrium deviation calculates how far choice is from the minimum of the group. This measure does not capture the distance from the subject’s current choice and the revision equilibrium.

A comparison of the treatments clearly reveals that S-CT falls short of RM on all four of these measures. In particular, the average minimum effort is lower (4.61 vs. 5.83), as are the average frequency of efficient effort (0.44 vs. 0.78) and the average fraction of fully coordinated groups (0.28 vs. 0.66). In contrast, the average group equilibrium deviation is higher in S-CT (0.86 vs. 0.49). We reject the hypothesis of equal distributions for all measures using Mann–Whitney U (MWU) tests, with $p < 0.001$, using the group average as a unit of observation.

We run a regression analysis with payoffs and the four measures listed above as endogenous variables. We cluster standard errors at the group level, so that one group is treated as one independent observation. The results of the regression analysis are presented in Table 2. The control group is S-CT treatment. Baseline and S-CT perform similarly on payoffs, minimum effort and frequency of efficient effort. Note that S-CT leads to significantly more fully coordinated groups and lower equilibrium deviation than Baseline. The regression highlights that RM performs better than the two treatments on aggregate level and on all four measures we focus on. Note that there are eight groups in the S-CT treatment, and therefore, some results are only marginally significant with errors clustered at the group level.

Finally, we run two alternative regression analyses of the five outcome variables, displayed in Tables 7 and 8 in Appendix E.3. We compare the treatments that incorporate the revision mechanism with those that introduce cheap talk.²⁴ We begin by comparing RM with

²⁴ By combining more treatments, we increase the number of independent observations (groups). The second set of regressions has 16 groups in RM and 24 in S-CT and R-CT, and the third set of regressions has 32 groups

Table 2: Regression Analysis

DEPENDENT VARIABLE:					
	<i>Payoffs</i>	<i>Minimum Effort</i>	<i>Freq Efficient Effort</i>	<i>Full Coordination</i>	<i>Eqbm Deviation</i>
Baseline	-0.168 (0.124)	-1.025 (0.750)	-0.173 (0.125)	-0.250** (0.116)	0.589** (0.268)
Revision Mechanism	0.210* (0.120)	1.213* (0.712)	0.339** (0.139)	0.388*** (0.141)	-0.395* (0.221)
Quiz	-0.034 (0.027)				-0.079 (0.092)
Constant	1.017*** (0.190)	4.612*** (0.618)	0.442*** (0.122)	0.275** (0.115)	0.840 (0.714)
R ²	0.213	0.200	0.313	0.305	0.094
Observations	1920	320	320	320	1920
Demographics	Yes	NA	NA	NA	Yes

Note: Standard errors clustered at the group level are in parentheses; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Reference category is Standard Cheap Talk treatment;

Payoffs variable is a subject payoff in a round. *Minimum Effort*, *Freq Efficient Effort*, *Full Coordination* are a group level measures and subject demographic information is not applicable. *Eqbm Deviation* is a subject level variable.

standard cheap talk and revision cheap talk jointly. In the last regression, we compare all of the revision mechanism treatments (RM, R-RM, and RM-VHBB) with the control group of all treatments that incorporate cheap talk (S-CT, R-CT, and R-R-CT). In all regressions, errors are clustered at the group level. All regression analyses indicate the same outcome: revision mechanisms significantly outperforms cheap talk treatments. This result can be observed in players' payoffs and in the four measures we focus on.

Result 1 *The revision mechanism significantly increases efficiency. This result is achieved through increases in the minimum effort chosen by the group as well as by the overall coordination on any effort profile.*

5.2 Evaluating exact predictions of the revision mechanism

We proceed by testing the exact predictions listed in Section 3.3. We restate them and test each one separately. The first exact prediction is that subjects' payoffs should be close enough to the efficient payoff. Or, alternatively, efficiency of the revision mechanism should be 100%. Recall that efficiency of RM is 82.1%, which is significantly lower than 100% with $p < 0.01$. The second exact prediction is that subjects' initial effort choice should be

in RM, R-RM, and RM-VHBB, and 32 groups in S-CT, R-CT, and R-R-CT.

the efficient effort. We test whether the fraction of subjects initially choosing 7 is 100%. In the last round, 93.8% of players' initial choices are the efficient effort. On average, 85.7% of the initial choice is the efficient effort, which is significantly lower than 100% with $p < 0.01$.

Result 2 *The revision mechanism achieves significantly lower payoffs than the efficient payoff, and the frequency of initial choice of efficient effort is significantly lower than 100%.*

The evidence is not sufficient to support the exact theoretical predictions of the asynchronous revision mechanism; we see that subjects' behavior is significantly different from the predictions. Given the specificity of the predictions, some distance between subjects' behavior and the point predictions is expected, in some sense. For instance, Nash equilibrium dictates that, even in the Baseline treatment, all subjects should choose the same effort. In Baseline, however, the groups fully coordinated on an effort choice (any effort profile, not necessarily efficient) in only 2 out of 80 cases. Similar low full coordination results are found in the literature; for example, in [Van Huyck et al. \(1990\)](#), out of 70 cases, there is 0 cases with full coordination. In the baseline treatment for minimum-effort game of [Blume and Ortmann \(2007\)](#), in 3 out of 32 cases do the groups fully coordinate on an effort level.²⁵

5.3 Evaluating the general insights from the theoretical framework

With the goal of understanding how the revision mechanism affects subjects' behavior in the laboratory and, in particular, to determine whether such effect can be attributed to the forces behind the theoretical results, we now turn our attention to the six general insights presented in Section 3.3. We start with the two insights related to the robustness of the theory.

5.3.1 Robustness to exogenous initial choices and to different payoff parameters

The theory postulates that, if the initial choices for the players are picked at random, then—with a long enough pre-play phase—the same outcome should occur as with endogenous initial choice, with a probability close to 1. This prediction provides a robustness check of our main treatment, and we test it by comparing RM with the R-RM treatment. Moreover, the R-RM treatment creates variance in the initial choice that we lack in the revision mechanism

²⁵ In our paper, we have 8 groups in the Baseline treatment. Each group plays 10 rounds, hence we have 80 cases to consider. [Van Huyck et al. \(1990\)](#) have 7 groups comparable to our paper with 10 rounds each. In [Blume and Ortmann \(2007\)](#), there are 4 groups for their baseline treatment for the minimum-effort game and each group plays 8 rounds. It is worth noting that in [Van Huyck et al. \(1990\)](#), the groups are considerably larger (groups of 14-16) than in both, current paper (groups of 6) and [Blume and Ortmann \(2007\)](#) (groups of 9).

as 86% of all initial choices are the efficient effort (i.e., 7).²⁶ We explore this variance in initial choices to analyze the dynamic best-response behavior of our subjects (see Section 5.3.4).

We find that the RM and R-RM treatments lead to similar behavior in all dimensions. We find no statistically significant difference in efficiency, with R-RM achieving 77.8% efficiency compared with 82.1% in RM. Not only is the average payoff similar (10.43 vs. 10.93), but the average minimum effort (5.54 vs. 5.83), the average frequency of efficient effort (0.71 vs. 0.78), the average fraction of fully coordinated groups (0.60 vs. 0.66), and the average equilibrium deviation (0.57 vs. 0.49) are both statistically and economically indistinguishable. We cannot reject MWU tests of equal distributions for any of the five measures, with $p = 0.173$, $p = 0.169$, $p = 0.152$, $p = 0.343$, and $p = 0.319$, respectively. See Tables 5 and 6 in Appendix E.2.

We now focus on the robustness of the prediction to different payoff specifications. As discussed in Section 3.3, within certain limits, we should expect similar outcomes for different payoff parameters. Solving the game backwards, as detailed in Appendix B, shows that for the payoff parameters from the original experiment on the minimum effort game, Van Huyck et al. (1990), the efficient profile is the unique revision equilibrium.

Our data indicates that the RM and RM-VHBB treatments lead to similar behavior in most dimensions. We find no statistically significant difference in efficiency, with R-RM achieving 82.2% efficiency compared with 82.1% for RM. Not only is the efficiency similar, but the fraction of fully coordinated groups (0.61 vs. 0.66) and the average equilibrium deviation (0.40 vs. 0.49) are both statistically and economically indistinguishable. We cannot reject MWU tests of equal distributions for these two measures, with $p = 0.447$ and $p = 0.772$. The minimum effort is marginally lower in RM-VHBB (5.44 vs. 5.83), with $p = 0.061$ and the frequency of efficient effort is significantly lower (0.59 vs. 0.78), with $p < 0.01$.

Result 3 *Subjects' performance in the revision mechanism is invariant to having exogenous initial choices and to a different set of payoff parameters.*

²⁶ In the R-RM treatment, the initial effort was determined at random. The distribution of initial efforts over rounds: 7% were 1; 13%, 2; 25%, 3; 13%, 4; 18%, 5; 13%, 6; and 10%, 7. It is clear that this different pattern is very different from the initial choices of RM. In RM, the distribution of the initial choices was 1% were 1; 1%, 2; 1%, 3; 1%, 4; 4%, 5; 6%, 6; and 86%, 7.

5.3.2 Frequency and asynchronicity of revision opportunities

In Section 3.3, we discuss two elements that are central to the equilibrium selection result: the frequency and the asynchronicity of the revision opportunities. These two elements are key for the backward induction argument used to select a unique revision equilibrium outcome in Proposition 1. We now test the empirical importance of these two elements.

We observe that I-RM leads to significantly lower efficiency, 69.6%, compared with 82.1% in RM. Moreover, subjects' performance in I-RM falls short of the performance in RM on every one of the other five measures we consider. In particular, the average payoff is lower (9.47 vs. 10.93), and so is the average minimum effort (4.99 vs. 5.83), the average frequency of efficient effort (0.49 vs. 0.78), and the average fraction of fully coordinated groups (0.39 vs. 0.66). In contrast, the average equilibrium deviation is higher in I-RM (0.78 vs. 0.49). We reject the hypothesis of equal distributions for each of the five measures using MWU tests, with $p < 0.001$. Based on the evidence, we conclude that the gradual commitment that is present in RM, but not in I-RM, is needed for subjects' higher payoff and for them to coordinate more often on the efficient equilibrium.

The evidence indicates that asynchronicity is a relevant factor underlying the success of the revision mechanism. We find that subjects' behavior in S-RM leads to significantly lower efficiency than in RM, 67.1%, compared with 82.1%. Furthermore, subjects' performance in S-RM is worse than the performance in RM for every one of the other five measures we consider. In particular, the average payoff is lower (9.47 vs. 10.93), and so is the average minimum effort (4.99 vs. 5.83), the average frequency of efficient effort (0.49 vs. 0.78), and the average fraction of fully coordinated groups (0.39 vs. 0.66). However, the average equilibrium deviation is higher in S-RM compared with RM (0.69 vs. 0.49). We reject the hypothesis of equal distributions for payoffs, minimum effort, and frequency of efficient effort measures using MWU test, with $p < 0.001$, and for fully coordinated groups and equilibrium deviation measure using MWU test, with $p = 0.003$ and $p = 0.006$, respectively.

Result 4 *The frequency and asynchronicity of revisions are relevant components for the success of the revision mechanism.*

5.3.3 The importance of commitment

The fifth insight discussed in Section 3.4 highlights that, although players can use revisions to communicate with other players, a revision is not cheap-talk communication. In the proof of

Proposition 1, it is key that players do not treat their own preparations—or others’ prepared actions—as cheap talk.

Comparing the performance of the R-CT treatment with RM empirically highlights the importance of commitment. While R-CT reaches 67.2% of efficiency, RM reaches 82.1%. Accordingly, subjects’ performance in R-CT is worse than the performance in RM on every one of the other five measures we consider. We find that R-CT leads to lower payoffs (9.19 vs. 10.93), as well as lower minimum effort (4.86 vs. 5.83), lower frequency of efficient effort (0.55 vs. 0.78), and lower fraction of fully coordinated groups (0.32 vs. 0.66). Furthermore, R-CT leads to a significantly higher equilibrium deviation compared with RM (0.97 vs. 0.49). Aligned with this, we reject the hypothesis of equal distributions for all five measures using MWU tests, with $p < 0.001$.

Result 5 *The commitment in the revision mechanism is a relevant factor for the success of the mechanism.*

5.3.4 The best response dynamics

The proof of Proposition 1 and the numerical exercise in Appendix B highlight that a player’s best response depends not only on the effort profile of other agents, but also on the time left before the deadline. The sixth general insight provided by the theoretical framework and discussed in Section 3.3 captures this intuition.

We now look at subjects’ dynamic behavior in RRM and classify all the revisions taken into three categories—forward-thinking, myopic down, and others—detailed below. We display in Figure 4 the types of moves taken as a function of the amount of time that has passed in the pre-play phase.

- (i) **Forward Thinking:** moves that would decrease the player’s payoff if they occur in the last instant; however, these moves will increase the payoff if other players follow. This category combines two types of moves: (1) the subject’s current choice is above the group’s minimum, but they still increase their chosen effort; and (2) the subject’s choice is the group’s minimum, and they increase their effort above the second minimum effort.
- (ii) **Myopic Down:** moves decreasing the player’s effort that would increase their payoff if the moves occur in the last instant. This category contains the moves that get the subject’s effort closer to the group minimum.

(iii) **Other:** moves not included in the above categories. This includes moves increasing the subject’s effort choice, which would increase their payoff, and moves decreasing the subject’s effort choice, which would decrease their payoff (e.g., because the subject is already at the group minimum or moves below the current minimum).

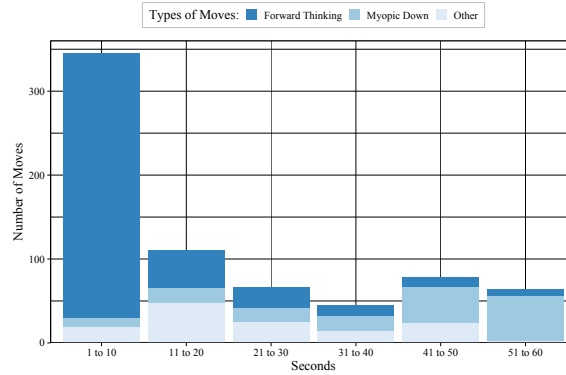


Figure 4: Classification of moves over time

In Figure 4, we document that the subjects consistently use revisions to communicate. Although players have about the same number of revision opportunities earlier or later in the round, they utilize the earlier revisions more frequently. In the first 10 seconds of the round, subjects used similar amount of revision opportunities than in the last 50 seconds combined.

When far from the deadline, the primary way in which players communicate through revisions is by using forward-thinking moves.²⁷ In the first 10 seconds of a round, more than 300 revision opportunities were used for forward-thinking moves, representing around 92% of all the revision opportunities taken. Figure 4 indicates that, if a revision opportunity arrived close to the deadline, the subject revised their prepared effort down, closer to the current minimum effort. In the last 10 seconds, about 85% of the revision opportunities taken were used for myopic down moves. It is necessary to emphasize, however, that subjects did not use all early opportunities to revise the prepared effort to the highest effort immediately, as predicted by the theory. More precisely, we observe that 78.2% of revisions taken in the first 10 seconds were used to revise the effort choice to 7, which is significantly lower than

²⁷ This idea of communicating intentions is similar to the concept of teaching other players how to play. Hyndman et al. (2012) study the influence of “teachers” in leading to Nash play.

100%. Given the evidence, the subjects' behavior is largely aligned with the general insight of the theory, even if significantly different from the point prediction.

Result 6 *In the revision mechanism, early revisions are forward thinking, while late revisions are myopically payoff-improving.*

5.4 Communication and Commitment

We now shift from the theoretical insights to focus on how subjects communicate in different treatments. In particular, we examine three aspects: how commitment affects communication, the differences between communication and actions in the cheap talk treatments, and the impacts of a richer message space.

Effects of commitment on communication Commitment affects communication in two interconnected ways. First, commitment makes communication more credible, with subjects acting differently in the presence of commitment after a particular profile is revealed. Second, commitment changes the optimal communication in that subjects communicate differently in the presence of commitment. Below, we try to parse these two distinct, but interconnected forces.

We first compare the credibility of messages in RM and in R-CT. To do so, we follow the theoretical discussion in [Blume \(1998\)](#), and we examine whether the whole group converging on a particular message profile makes that effort profile (an equilibrium in the component game) more salient. We look at all groups that converged to stating their intention to choose the same effort level (not necessarily the efficient effort profile). Out of all the times that a group converged to a common effort profile during the 60 second pre-play, that profile was implemented at the payoff-relevant moment in 87.6% of these rounds in RM, compared with 51.1% in R-CT.

We now focus on how commitment affects what is communicated. In [Figure 5a](#), we display the average equilibrium deviation of the posted efforts over the 60-second interval.²⁸ The graph shows a clear decline in the equilibrium deviation over the pre-play in RM, as players coordinate more. More importantly, we see a clear difference between RM and R-CT, especially in the latter part of the pre-play phase. Facing a group member who is

²⁸ In [Figure 5](#), we use the last five of the total 10 rounds. In [Appendix E](#), we present the graph for all 10 rounds ([Figure 8](#)) and additional treatment, R-R-CT.

choosing a smaller effort close to the deadline, a subject reduces their chosen effort (thus reducing the equilibrium deviation) in RM, but not in R-CT. In the absence of commitment, lowering the choice of effort is unnecessary because revising it in the final instant is possible.

Result 7 *Convergence to a common message leads to more credibility of the communication in the presence of commitment.*

Differences between communication and action As Result 7 documents, in the revision cheap talk treatment, subjects' communication has significantly less credibility. Furthermore, we document significant differences between the profile communicated in the last instant of the pre-play phase and the payoff-relevant effort choices in cheap talk treatments. As depicted in Figure 5b, both the average effort and the fraction of fully coordinated groups of the payoff-relevant profile are significantly lower than those of the 60th second profile. Furthermore, we compare the five measures we use throughout the paper between payoff-relevant efforts in R-CT and 60th second message in R-CT. The average payoff is lower (9.194 vs. 10.18), as are the average minimum effort (4.9 vs. 5.5), the average frequency of efficient effort (0.56 vs. 0.77), and the average fraction of fully coordinated groups (0.32 vs. 0.48). However, the average equilibrium deviation is similar (0.97 vs. 0.92). We reject the hypothesis of equal distributions for payoffs, minimum effort, and frequency of efficient effort measures using the MWU test, with $p < 0.001$, and for fully coordinated groups using the MWU test, with $p = 0.002$. We cannot reject the equal distribution hypothesis of equilibrium deviation, as the MWU leads to $p = 0.103$. The difference between the messages and actions leads to 10.7% loss in payoffs.

Result 8 *Substantial differences exist between the preparations at the last second and the effort implemented in the absence of commitment.*

Richness of communication The differences in subjects' behavior between the revision mechanism and revision cheap-talk, combined with the results above, indicate that repeated communication of intended actions plays a limited role in aiding subjects to better coordinate on a higher effort profile in the minimum-effort game. Results 7 and 8 point to the lack of credibility of the messages as a possible culprit. One possible source for this is that players do not believe others' communication since they cannot distinguish positive communication about intentions ("I intend to play...") from normative communication about the group's

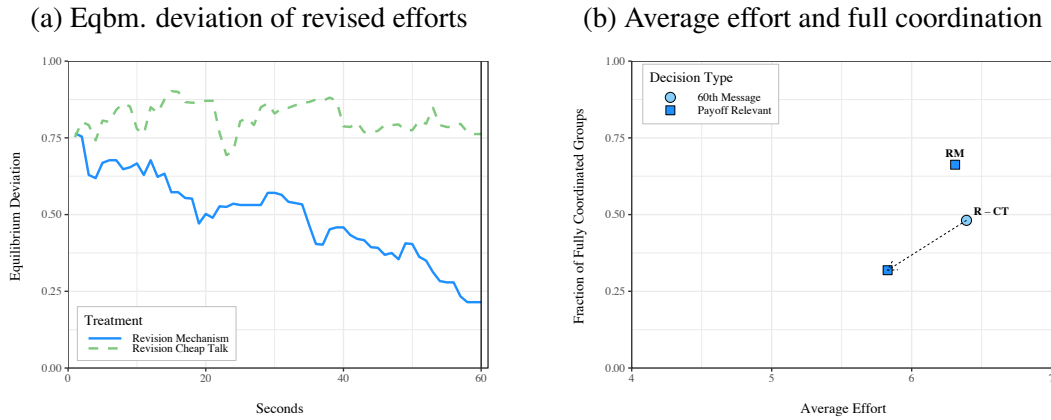


Figure 5: Equilibrium Deviation over Time

effort profile (“We should all coordinate on...”). We now consider whether enriching the message space to include a second message, “I think we should all choose,” can improve coordination.

We find that R-CT and R-R-CT treatments lead to similar behavior in all dimensions. Not only is the average payoff similar (9.20 vs. 9.32), but the average minimum effort (4.86 vs. 4.94), the average frequency of efficient effort (0.56 vs. 0.59), the average fraction of fully coordinated groups (0.32 vs. 0.36), and the average equilibrium deviation (0.97 vs. 0.96) are statistically indistinguishable. We cannot reject MWU tests of equal distributions for any of the five measures, with $p = 0.685$, $p = 0.672$, $p = 0.385$, $p = 0.499$, and $p = 0.687$, respectively. Finally, R-R-CT performs significantly worse on all five measures compared with RM.

Result 9 *Enriching the cheap-talk messages to include explicitly labelled messages about the group choice does not significantly improve subjects’ payoffs.*

We now consider the credibility of messages in R-R-CT treatment. We find that, when subjects converged to a common intention in a group message, they followed through and fully coordinated 54.2% of the time. This percentage increases to 63.4% when we calculate not only group message, but the convergence of intention messages as well. That is, if both intention and group messages converged, then 63.4% of the time the payoff-relevant efforts were also the same. Recall, the credibility rate in R-CT and RM, are 51.1% and 87.6%, respectively. Another interesting result in R-R-CT is the difference between the individual

and group messages. What subjects state they all should do is significantly higher than what they say they intend to do. We conjecture that the difference highlights subjects' willingness to coordinate; however, without some assurances (as the incremental commitment in RM, for instance), the communication in the cheap-talk treatments is insufficient.

6 Concluding Remarks

Coordination environments are prevalent in real-world situations, and coordination failures leading to inefficiencies are widespread. In this paper, we provide experimental evidence that in a particular coordination game—the minimum-effort game—commitment-enhanced communication can significantly reduce the coordination failures. While the evidence strongly supports the overall effectiveness of the novel mechanism examined in this paper, the specific predictions are not fully supported. Given the specific nature of the exact predictions, some discrepancy between the point predictions and empirical evidence is not unusual. We further analyze insights of the model and document the aspects of the mechanism that are critical for its success and other features to which the outcomes are invariant. Taken together, the empirical evidence indicates that subjects' behavior in the lab is largely aligned with the theoretical predictions.

What are the reasons in the model that may lead to some divergence between the point predictions and subjects' behavior? Let us discuss some speculative hypotheses that future work could explore. One possibility is that not all subjects do the equilibrium calculations when the dynamic game starts; instead, they gradually learn to coordinate. They might do so by learning about others in the group or by learning about the game itself. Another possible framework would be a lack of common knowledge of essential elements of the setting. In particular, in the model, we assume common knowledge of the structure and of payoffs; thus, the only source of uncertainty is strategic uncertainty. However, that may not be the case for some subjects in the lab. Players might be uncertain about other dimensions of the game that are necessary for equilibrium reasoning. While we recognize these alternative frameworks, we cannot empirically test them in the current paper and we leave it for future research. In this paper, we set out to examine the efficacy of a novel mechanism and to find which aspects are responsible for its success.

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Appendices

A Proofs

Similar to the proof in [Calcagno et al. \(2014\)](#), ours relies on a backward-induction argument. In the first step of the proof, we show that the Pareto-dominant equilibrium profile \bar{e} is absorbing in the revision game. If all players choose the maximal effort, then, for any following subgame, the unique subgame perfect equilibrium is for all players to play \bar{e} . More formally, we show that, at a certain period, it is true that if all other players are preparing \bar{e}_{-i} , player i will prepare \bar{e}_i if they have a revision opportunity. In the period immediately before, if all other players are preparing \bar{e}_{-i} , player i will prepare \bar{e}_i if they have a revision opportunity.

If only two players are present, this would constitute the whole argument because one player would always be in the position to induce the other player to prepare the maximum effort. However, $n > 2$ complicates the matter, as the unraveling argument is not trivial. We show that the condition $(n - 2)K < (n - 1)$ is sufficient to have a lower bound on players' payoff of choosing the efficient action converging to the efficient payoff. Thus, at the end of the countdown, all players prepare the maximal effort with probability $1 - \varepsilon$.

Proof. Let $\underline{v}_i^t(k)$ be the infimum of player i 's payoff at t in subgame perfect equilibrium strategies and histories such that there are at least k players who prepare the action \bar{e} , and no player receives a revision opportunity at t . By mathematical induction with respect to $k = n, n - 1, \dots, 0$, we show that $\lim_{t \rightarrow -\infty} \underline{v}_i^t(k) = \pi_i(\bar{e}), \forall i$. Step 1 below shows the proof for $k = n$.

Step 1 Consider the final period. All $-i$ players are preparing the profile \bar{e}_{-i} and i has a revision opportunity. It is optimal for player i to prepare \bar{e}_i , as this leads to a higher payoff than any other possible effort choice (\bar{e} is the Pareto-dominant profile and is an equilibrium).

Now, for the inductive step, consider any period τ after t . If all $-i$ players are preparing the profile \bar{e}_{-i} and i has a revision opportunity, it is optimal for player i to prepare \bar{e}_i . Consider also that, at the period immediately before t , $t - 1$, all $-i$ players are preparing the profile \bar{e}_{-i} and i has a revision opportunity. If player i prepares \bar{e} , then they are guaranteed payoff $\pi_i(\bar{e})$. If player i prepares any other action e , their expected payoff can be bounded by $(1 - (1 - \frac{\rho}{n})^{-t})\pi_i(\bar{e}) + (1 - \frac{\rho}{n})^{-t}(\pi_i(\bar{e}) - \alpha) < \pi_i(\bar{e}) \forall t$, where the bound is obtained by considering that $(i) \pi_i(\bar{e}) - \alpha$ is the second-best payoff for player i , (ii) with probability

$(1 - \frac{p}{n})^{-t}$ player i gets no revision opportunity before the deadline, and (iii) all other players continue to exert maximal effort. This concludes step 1.

Step 2 (inductive argument) Suppose that $\lim_{t \rightarrow -\infty} \underline{v}_i^t(k+1) = \pi_i(\bar{e})$, $\forall i$, with $k+1 \leq n$; we will show that $\lim_{t \rightarrow -\infty} \underline{v}_i^t(k) = \pi_i(\bar{e})$, $\forall i$.

Consider an arbitrary $\varepsilon > 0$. Since $\lim_{t \rightarrow -\infty} \underline{v}_i^t(k+1) = \pi_i(\bar{e})$, $\forall i$, a finite T_0 must exist such that $\forall t \leq T_0$, $\underline{v}_i^t(k+1) \geq \pi_i(\bar{e}) - \varepsilon \forall i$. Consider that k players prepare \bar{e} at a time t before the said T_0 , that is, $t = T_0 + \tau_1$ with $\tau_1 \leq 0$. Then, if player j who is not preparing \bar{e} at time t can move first by T_0 , they yield at least $\pi_j(\bar{e}) - \varepsilon$ by preparing \bar{e}_j . This outcome implies that each player i will at least yield $\pi_i(\bar{e}) - K\varepsilon$. Therefore, we can define a lower bound for a player's utility if k players are preparing \bar{e} at time t :

$$\underline{v}_i^t(k) \geq \frac{1}{n}(1 - (1-p)^{\tau_1})(\pi_i(\bar{e}) - K\varepsilon) + (1 - \frac{1}{n}(1 - (1-p)^{\tau_1}))\underline{\pi}_i(e) \forall i,$$

where $\frac{1}{n}(1 - (1-p)^{\tau_1})$ is the probability that there is a revision and a particular player j who is not preparing \bar{e} at that time is the first to get a revision before time T_0 . We also assume that if such a move does not occur, the worst possible payoff will happen.

If τ_1 is a sufficiently long time interval, then there exists finite T_1 such that for all $\tau_2 \leq 0$, if the period is far removed from the deadline; $t = T_0 + T_1 + \tau_2 \leq T_0 + T_1$, then $\underline{v}_i^t(k) \geq \frac{1}{n}\overline{\pi}_i(e) + (1 - \frac{1}{n})\underline{\pi}_i(e) - K\varepsilon \forall i$. Introducing a bit of notation, we can define $\alpha_1 = \frac{1}{n}$, and $\underline{v}_i^t(k) \geq \alpha_1\overline{\pi}_i(e) + (1 - \alpha_1)\underline{\pi}_i(e) - K\varepsilon \forall i$

For $t = T_0 + T_1 + \tau_2$ we can find a lower bound on players' payoff $\underline{v}_i^t(k)$ in different cases:

1. If j moves first by $T_0 + T_1$, then a lower bound on player i 's payoff depends on whether or not j is preparing \bar{e}_j .
 - If j is not preparing \bar{e}_j at time t , then a lower bound on player i 's payoff is $\pi_i(\bar{e}) - K\varepsilon$ as before.
 - If j is preparing \bar{e}_j at time t they will move first by $T_0 + T_1$; then, a lower bound on player j 's payoff is given by $\frac{1}{n}\pi_j(\bar{e}) + (1 - \frac{1}{n})\underline{\pi}_j(e) - K\varepsilon$ by the same reasoning as before. This implies that for player i , a lower bound on their payoff is given by $(1 - K(1 - \frac{1}{n}))\pi_i(\bar{e}) + K(1 - \frac{1}{n})\underline{\pi}_i(e) - K^3\varepsilon$.

2. If i will move first by $T_0 + T_1$, then a lower bound depends on whether or not they are preparing \bar{e}_i .

- If they are one of the k preparing \bar{e} , then a lower bound is given by $\frac{1}{n}\pi_i(\bar{e}) + (1 - \frac{1}{n})\pi_i(e) - K\varepsilon$.
- If they are not one of the k preparing \bar{e} , by doing a revision, they can guarantee, by the inductive hypothesis, at least $\pi_i(\bar{e}) - \varepsilon$.

In total, player i 's payoff satisfies:

$$\begin{aligned} \underline{v}_i^t(k) &\geq \frac{1}{n}(1 - (1 - p)^{\tau_2})(\pi_i(\bar{e}) - K\varepsilon) \\ &\quad + (\frac{1}{n}(1 - (1 - p)^{\tau_2}) + (1 - p)^{\tau_2})(\frac{1}{n}\pi_i(\bar{e}) + (1 - \frac{1}{n})\pi_i(e) - K\varepsilon) \\ &\quad + (1 - \frac{2}{n})((1 - (1 - p)^{\tau_2}))(1 - K(1 - \frac{1}{n}))\pi_i(\bar{e}) + K(1 - \frac{1}{n})\pi_i(e) - K^3\varepsilon, \forall i \end{aligned}$$

Taking a sufficiently long τ_2 , there exists a finite T_2 such that at $t = T_0 + T_1 + T_2 + \tau_3$ with $\tau_3 \leq 0$, we have that

$$\begin{aligned} \underline{v}_i^t(k) &\geq (\frac{1}{n} + \frac{1}{n^2} + (1 - \frac{2}{n})(1 - K(1 - \frac{1}{n})))\pi_i(\bar{e}) \\ &\quad + (1 - \frac{1}{n} + \frac{1}{n^2} + (1 - \frac{2}{n})(1 - K(1 - \frac{1}{n})))\pi_i(e) - K^3\varepsilon, \forall i \end{aligned}$$

defining $\alpha_2 = \frac{1}{n} + \frac{1}{n^2} + (1 - \frac{2}{n})(1 - K(1 - \frac{1}{n}))$, we have the second step $\underline{v}_i^t(k) \geq \alpha_2\pi_i(\bar{e}) + (1 - \alpha_2)\pi_i(e) - K^3\varepsilon \forall i$.

Recursively, for each $M = 1, 2, \dots$, there exists T_0, T_1, \dots such that $t \leq T_0 + T_1 + \dots + T_M$,

$$\underline{v}_i^t(k) \geq \alpha_M\pi_i(\bar{e}) + (1 - \alpha_M)\pi_i(e) - K^{2M-1}3\varepsilon \forall i.$$

with $\alpha_M = \frac{1}{n} + \frac{1}{n}\alpha_{M-1} + (1 - \frac{2}{n})(1 - K(1 - \alpha_{M-1}))$.

The condition in Proposition 1 is sufficient to guarantee that α_M is monotonically increasing and converges to 1. Taking a large enough T yields the result. ■

B Numerical solution of the discrete time revision game

In this section, we explain the backward-induction procedure to solve the game for the specific parameters given in our experiment. We consider a particular payoff specification following our experimental setup: a triple of linear coefficients γ , α , and β ; a given number of players n ; a given set of actions E ; a pre-play length T ; and a given revision probability, p . We solve the game for the expected payoff of every player at any time $-t \in \{-T, -(T-1), \dots, -1, 0\}$, for every strategy profile. We also obtain the transition probability from any strategy profile to any other strategy profile between any two periods.

At the deadline ($t = 0$): We construct an n -tuple vector with dimension $|E|^n$, called V_0 . Each line of V_0 has the payoff of each player if a particular strategy profile, e , is played.

Before the deadline, $t \in [-T, 0)$: Consider a given vector V_{t+1} . An n -tuple of V_{t+1} has the expected payoff of all players at time $t+1$ if that particular strategy profile is prepared (given that all players maximize their payoff if they have a revision in the future). We proceed backwards inductively, given the vector V_{t+1} , we construct V_t in the following way. First, for any strategy profile, we can compute how a player would revise their effort choice. That is, if player i had a revision opportunity, which effort would they choose, given that their expected payoffs of different action profiles are given by the vector V_{t+1} . This gives us the auxiliary matrix V_t^{rev} , a $|E|^n \times n$ matrix of n -tuples. Each element of the matrix gives us the payoff of all players if the strategy line were in place, and the player column had a revision opportunity at time t . The vector V_t is obtained by $(1-p) \times V_{t+1} + \frac{p}{n} \times V_t^{rev} \times \mathbf{1}_{n \times 1}$, where the first term is obtained when no one has a revision (and, thus, the strategy profile is unchanged), and the second term is the expected value of the payoff for each player given that someone has received a revision opportunity. We can iterate this process until V_{-T} .

Using the numerical solution to verify the proposition: For a particular set of parameters, γ , α , β , n , $|E|$, T , p , we say that Proposition 1 holds if, for a finite $\bar{T}(\gamma, \alpha, \beta, n, |E|, p) < T$, when a player has a revision opportunity, they choose \bar{e}_i independent of the effort profile in place. That is, for all $t > \bar{T}$, playing \bar{e}_i dominates any other effort choice, and all elements of the matrix V_t^{rev} are equal to $\pi_i(\bar{e})$. For the first part of Proposition 1, note that for any given $\varepsilon > 0$, if $T' \geq \bar{T} + \tau$, then the profile \bar{e} is played with probability larger than $1 - \varepsilon$. The integer τ is defined as the minimum interval of time such that the probability

that all players have at least one revision opportunity in that interval is larger than $1 - \varepsilon$; that is, τ is the smaller integer that solves $(1 - (1 - \frac{p}{n})^\tau)^n \leq 1 - \varepsilon$. We can see that the time interval needed, τ , increases with the number of players and decreases with the probability of a revision being awarded. For the second part of Proposition 1, it is sufficient that $T' \geq \bar{T}$. Note that the condition specified on the propositions is sufficient, but not necessary for the particular payoff parameters used in this paper.

Going beyond the proposition: As a byproduct of the construction of V_t from V_{t+1} , we also obtain a transition matrix, M_t , with dimensions $|E|^n \times |E|^n$, that specifies for any strategy profile today the probability that each profile will be chosen in the next period. For any given set of parameters, given a distribution of effort profiles at time $-T$, $e(-T)$, we can calculate the final distribution of efforts, at time 0, for any length of the pre-play phase, $e(-T) \times \prod_{s=-T}^0 M_s$.

The two plots in Figure 6 highlight how the probability of a revision, p , changes the expected results of the game. We focus on two key dimensions: (i) the number of periods needed for \bar{e} to be the dominant effort choice independent of the profile in place, \bar{T} ; and (ii) the probability of the profile \bar{e} being chosen at the end of the countdown, given that $T = 60$ and the game was started with a profile chosen at random.

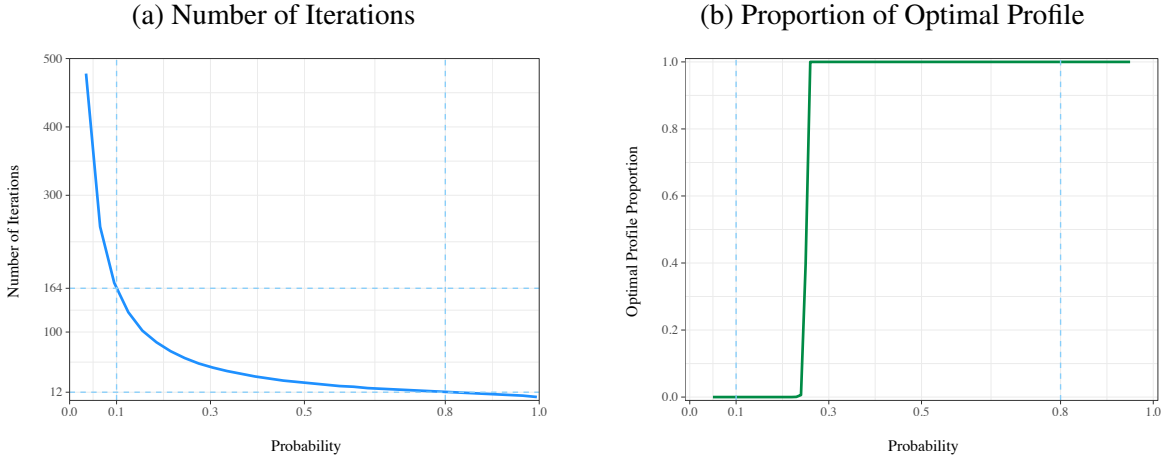


Figure 6: Numerical Solution Outputs

Finally, we re-do the numerical analysis above for payoff parameters in treatment RM-VHBB. We find that with revision opportunities arriving with 80% chance, 14 interactions

are sufficient for the uniqueness results to hold. Since the pre-play phase lasts 60 seconds, the theory predicts a unique revision equilibrium in the revision game and, hence, RM-VHBB results should be similar to those in RM.

C Survey results

At the end of the experiment, our subjects took a short survey recording their gender, major, GPA, and whether they had taken a game theory course. The summary is presented in Table 3.

Table 3: Survey Results

Variable:	%/pt
Gender	52
Game Theory	21
GPA	3.5
Major: Economics/Business/Finance	23
Major: Humanities	14
Major: Computer Science	8.7
Major: Media	5.5
Major: Psychology	4.4
Major: Mathematics	3.6
Major: Engineering	3.4
Major: Physics/Chemistry/Biology	3.2

D Evaluating the exact predictions for all treatments

In our paper, we highlight the exact theoretical predictions given the environment implemented in the RM treatment. In Section 5.2, we test these exact predictions. We now discuss exact predictions for other treatments. Given the multiplicity of equilibria displayed in many of the treatments (i.e. Baseline, S-CT, R-CT, R-R-CT, I-RM, and S-RM), we concentrate on predictions that hold for all pure strategy equilibria. For that, we focus on variables other than the effort profile chosen; instead, we concentrate on full coordination and on the actual revision process. Below, we describe exact theoretical predictions for all treatments and provide empirical tests for each one.

Coordination In all treatments, the theoretical prediction is that all groups should be fully coordinated at the payoff relevant choice.²⁹ In Table 4, we present the frequency of fully

²⁹ For R-RM, the prediction is that, with probability high enough the group should be fully coordinated. The exception of R-RM follows from the randomness introduced by exogenous initial choices and random revision

coordinated groups as well as the equilibrium deviation for the payoff relevant choices of each treatment.

Furthermore, for treatments with uncertainty regarding future revisions, we can go beyond predicting full coordination at the payoff relevant moment. The theoretical prediction is that full coordination should occur from the initial choices. This implies that, for I-RM, S-RM, RM, and RM-VHBB all groups should be fully coordinated from the initial choice

Table 4: Exact predictions and empirical evidence

<i>Treatment</i>	EMPIRICAL EVIDENCE					PREDICTION		
	<i>FC(PR)</i>	<i>ED(PR)</i>	<i>FC(I)</i>	<i>ED(I)</i>	<i>NRF</i>	<i>FC</i>	<i>ED</i>	<i>NRF</i>
Baseline	2.5	1.49	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
S-CT	27.5	0.86	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
R-CT	31.9	0.97	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
R-R-CT	36.2	0.96	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
I-RM	38.8	0.78	38.8	0.97	46.3	100	0	100
S-RM	46.2	0.69	30.0	1.29	25.0	100	0	100
R-RM	60.0	0.58	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
RM	66.2	0.49	50.6	1.04	42.5	100	0	100
RM-VHBB	61.3	0.40	45.0	1.08	42.5	100	0	100
Van Huyck et al. (1990) (B)	0	1.46	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
Blume and Ortmann (2007) (B)	12.5	1.74	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
Blume and Ortmann (2007) (C)	26.6	1.17	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
Deck and Nikiforakis (2012) (NT) ³⁰	37.0	0.87	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>
Weber (2006) (B)	1.7	1.5	<i>NA</i>	<i>NA</i>	<i>NA</i>	100	0	<i>NA</i>

Note: *FC* and *ED* stand for the percentage of fully coordinated groups and the average equilibrium deviation. *NRF* presents the frequency of no revision cases. That is, out of all groups and all rounds, in what fraction of cases did groups not revise (every member of a group kept their initial choice till the end of the phase). Finally, *PR* and *I* indicate whether the choice is payoff relevant or initial choice. *B* next to other papers stands for their baseline treatment results. *C* in Blume and Ortmann (2007) is for the communication treatment in the minimum effort game.

Revising Effort Choices The randomness and asynchronicity of the revision opportunity allow us to obtain additional predictions regarding the revision of effort choices. In the I-RM, RM, and RM-VHBB no player should ever revise their effort along the equilibrium path of any revision equilibrium. In any revision equilibrium of these games, players choose an initial effort configuration that is fully coordinated (in RM and RM-VHBB we can further pin down a unique profile, the efficient effort profile) and never revise their strategy. Please

opportunities. For instance, it is a possibility that the initial effort profile will not display full coordination and that no-player has any revision opportunity throughout the 60 seconds.

³⁰ For Deck and Nikiforakis (2012), we have the data from the Neighbourhood Treatment (NT), and the calculations in Table 4 are for that treatment only.

note that, since revisions are randomly and asynchronously awarded, they are not a feature of the equilibrium path of a revision equilibrium. Furthermore, for S-RM, revisions might be a part of the equilibrium path in a revision equilibrium. However, in any pure strategy revision equilibrium, at each revision opportunity either all players jointly revise their effort choices to a profile in which all choose the same effort or no player revise their effort choice and they remain all choosing the same effort level. Hence, one theoretical prediction is that a revision should only be used by a player to change her effort choice if all other players also use that same revision opportunity to change their effort choices.

In Table 4, we provide a test of these predictions. For the treatments I-RM, RM, and RM-VHBB we display the frequency of rounds in which a group does not utilize any revision. For the treatment S-RM, we display the frequency of rounds in which a group either does not utilize any revision or, if a subject utilizes that revision to change her effort choice, then all subject utilize the same revision opportunity.

Taken together, these tests highlight the lack of support for the exact predictions obtained from the theory, in all treatments. In the paper, when evaluating the predictions for RM, we state that the lack of support for exact theoretical predictions is, in some sense, expected given the specificity of such predictions and the simplicity of the equilibrium concepts used. To further substantiate this claim, we also evaluate the empirical support for exact theoretical predictions given the environment implemented in the lab in other papers in the literature.

Evaluating the exact predictions in the literature³¹ We now proceed to testing exact theoretical predictions using data for similar papers in the literature (see Table 4). The introduction of incremental commitment implying the selection of a unique outcome as the subgame perfect equilibrium outcome of the extended game is a novel point of our work, hence we must go beyond theoretical predictions about the effort profile. However, there are alternative dimensions that are clearly pinned down by the theory, even on papers that implement cheap talk communication. Following the same intuition as above, we focus on the prediction that all groups should be fully coordinated in the payoff relevant choice. We note that the prediction that, in all Nash equilibria of the normal form game, a group's effort profile should be fully coordinated holds for simultaneous play minimum effort games. Furthermore, that prediction cannot be altered by pre-play cheap talk communication.

³¹ We would like to thank the authors of the following papers for making their data available for the calculations in the current paper: [Weber \(2006\)](#), [Blume and Ortmann \(2007\)](#), and [Deck and Nikiforakis \(2012\)](#).

E Additional Tables, Figures and Discussions

In this section we provide more details on overall performance of all treatments, details on non-parametric tests, additional regression analyses, as well as some analyses of the behavior over 60-seconds and 10 rounds.

E.1 Overall performance of all treatments

Figure 7 presents two graphs highlighting the overall performance of all treatment on four dimensions: minimum effort, equilibrium deviation, average effort, and frequency of coordination on median action.

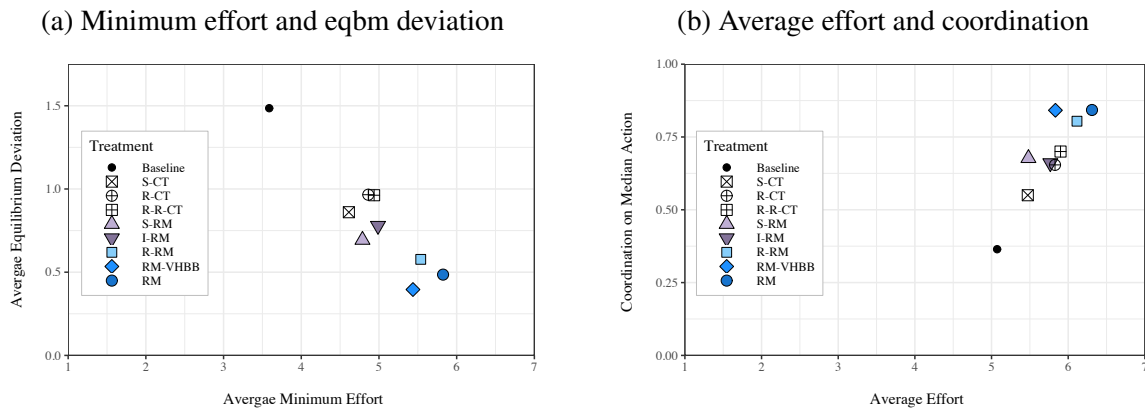


Figure 7: Overall performance of all treatments

E.2 Non-parametric test results

Table 5 includes average values of main five measures used throughout the paper. Table 6 presents test results of non-parametric MWU test p -values between RM and other treatments. We use group average as a unit of observation for all the tests in Table 6.

Table 5: Average values for focal variables

	Payoff	Minimum Effort	Freq 7s	Fully Coord	Eqbm Dev
Baseline	6.946	3.587	0.269	0.025	1.485
S-CT	8.836	4.612	0.442	0.275	0.860
R-CT	9.194	4.862	0.555	0.319	0.966
R-R-CT	9.315	4.938	0.598	0.362	0.963
I-RM	9.468	4.987	0.569	0.388	0.779
S-RM	9.183	4.787	0.490	0.463	0.694
R-RM	10.429	5.537	0.713	0.600	0.577
RM	10.926	5.825	0.780	0.662	0.485
RM-VHBB	11.042	5.438	0.590	0.613	0.396

Table 6: MWU test p -values (group average as a unit of observation)

RM vs.	Payoff	Minimum Effort	Freq 7s	Fully Coord	Eqbm Dev
S-CT	0.000	0.000	0.000	0.000	0.000
R-CT	0.000	0.000	0.000	0.000	0.000
R-R-CT	0.000	0.000	0.000	0.000	0.000
I-RM	0.000	0.000	0.000	0.000	0.000
S-RM	0.000	0.000	0.000	0.003	0.006
R-RM	0.173	0.169	0.151	0.343	0.319
RM-VHBB	0.260	0.061	0.003	0.447	0.772

E.3 Additional regression analyses

In this section we include additional regression analyses. First we present regressions with combined cheap-talk treatments and then combined revision mechanism treatments.

Table 7: Regression Analysis (S-CT and R-CT as reference)

DEPENDENT VARIABLE:					
	<i>Payoffs</i>	<i>Minimum Effort</i>	<i>Freq Efficient Effort</i>	<i>Full Coordination</i>	<i>Eqbm Deviation</i>
Baseline	-0.198** (0.088)	-1.190** (0.524)	-0.249*** (0.073)	-0.279*** (0.068)	0.536** (0.221)
Revision Mechanism	0.184** (0.080)	1.050** (0.468)	0.263*** (0.095)	0.358*** (0.104)	-0.447*** (0.160)
Constant	0.777*** (0.168)	4.780*** (0.309)	0.517*** (0.066)	0.304*** (0.066)	0.549 (0.441)
Quiz	0.002 (0.022)				0.010 (0.040)
R ²	0.141	0.138	0.204	0.215	0.0586
Observations	2880	480	480	480	2880
Demographics	Yes	NA	NA	NA	Yes

Note: Standard errors clustered at the group level are in parentheses; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Reference category is S-CT and R-CT combined;

Payoffs variable is a subject payoff in a round. *Minimum Effort*, *Freq Efficient Effort*, *Full Coordination* are a group level measures and subject demographic information is not applicable. *Eqbm Deviation* is a subject level variable.

Table 8: Regression Analysis (RMs vs CTs)

DEPENDENT VARIABLE:					
	<i>Payoffs</i>	<i>Minimum Effort</i>	<i>Freq Efficient Effort</i>	<i>Full Coordination</i>	<i>Eqbm Deviation</i>
Baseline	-0.209** (0.085)	-1.230** (0.502)	-0.269*** (0.061)	-0.294*** (0.055)	0.529** (0.219)
RMs	0.169*** (0.059)	0.837** (0.343)	0.178** (0.073)	0.316*** (0.072)	-0.457*** (0.130)
Constant	0.837*** (0.161)	4.820*** (0.272)	0.538*** (0.053)	0.319*** (0.053)	0.504 (0.401)
Quiz	-0.0002 (0.022)				0.021 (0.039)
R ²	0.122	0.102	0.126	0.173	0.0552
Observations	4320	720	720	720	4320
Demographics	Yes	NA	NA	NA	Yes

Note: Standard errors clustered at the group level are in parentheses; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Reference category is CTs, combining S-CT, R-CT, and R-R-CT; RMs combine RM, R-RM, and RM-VHBB;

Payoffs variable is a subject payoff in a round. *Minimum Effort*, *Freq Efficient Effort*, *Full Coordination* are a group level measures and subject demographic information is not applicable. *Eqbm Deviation* is a subject level variable.

Tables 9 and 10 present regression analyses for all treatments and round variable.

Table 9: Regression Analysis (all treatments)

	DEPENDENT VARIABLE:				
	<i>Payoffs</i>	<i>Minimum Effort</i>	<i>Freq Efficient Effort</i>	<i>Full Coordination</i>	<i>Eqbm Deviation</i>
Baseline	-0.177 (0.127)	-1.020 (0.744)	-0.173 (0.124)	-0.250** (0.115)	0.602** (0.269)
Revision Mechanism	0.211* (0.121)	1.210* (0.706)	0.339** (0.138)	0.388*** (0.139)	-0.383* (0.224)
Revision Mechanism VHBB	0.221** (0.109)	0.825 (0.661)	0.148 (0.154)	0.338*** (0.130)	-0.486** (0.205)
Random Revision Mechanism	0.159 (0.122)	0.925 (0.713)	0.271* (0.153)	0.325** (0.143)	-0.289 (0.232)
Infrequent Revision Mechanism	0.067 (0.150)	0.375 (0.874)	0.127 (0.167)	0.113 (0.162)	-0.076 (0.294)
Synchronous Revision Mechanism	0.037 (0.127)	0.175 (0.743)	0.048 (0.144)	0.188 (0.154)	-0.189 (0.254)
Revision Cheap Talk	0.039 (0.120)	0.250 (0.702)	0.114 (0.143)	0.044 (0.139)	0.100 (0.232)
Richer Revision Cheap Talk	0.047 (0.148)	0.325 (0.842)	0.156 (0.140)	0.088 (0.138)	0.084 (0.342)
Constant	0.779*** (0.158)	4.610*** (0.613)	0.442*** (0.121)	0.275** (0.114)	0.420 (0.391)
Quiz	0.002 (0.019)				0.026 (0.037)
R ²	0.104	0.0881	0.129	0.145	0.048
Observations	5280	880	880	880	5280
Demographics	Yes	NA	NA	NA	Yes

Note: Standard errors clustered at the group level are in parentheses; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Reference category is standard cheap talk S-CT;

Payoffs variable is a subject payoff in a round. *Minimum Effort*, *Freq Efficient Effort*, *Full Coordination* are a group level measures and subject demographic information is not applicable. *Eqbm Deviation* is subject level variable.

E.4 Equilibrium deviation and message to action dynamics

Figure 8a presents equilibrium deviation over 60 seconds (for 10 rounds) for 3 treatments. As we described in the main text, the main difference between RM and cheap-talk treatments is in the last 5-10 seconds. Figure 8b shows the movement from 60th second message in R-CT and R-R-CT to the payoff relevant efforts. It is worth noting how similar the results are for R-CT and R-R-CT.

Table 10: Regression analysis (all treatments and round variable)

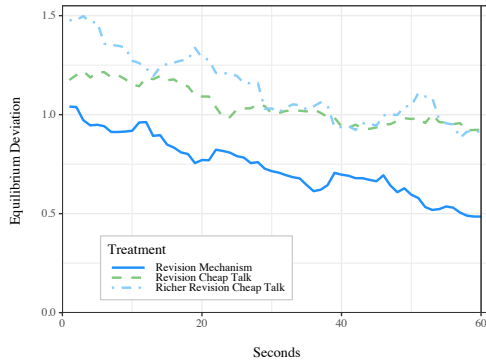
	DEPENDENT VARIABLE:				
	Payoffs	Minimum Effort	Freq Efficient Effort	Full Coordination	Eqbm Deviation
Baseline	-0.177 (0.127)	-1.020 (0.744)	-0.173 (0.124)	-0.250** (0.115)	0.602** (0.269)
Revision Mechanism	0.211* (0.121)	1.210* (0.707)	0.339** (0.138)	0.388*** (0.140)	-0.383* (0.224)
Revision Mechanism VHBB	0.221** (0.109)	0.825 (0.661)	0.148 (0.154)	0.338*** (0.130)	-0.486** (0.205)
Random Revision Mechanism	0.159 (0.122)	0.925 (0.713)	0.271* (0.153)	0.325** (0.143)	-0.289 (0.232)
Infrequent Revision Mechanism	0.067 (0.150)	0.375 (0.874)	0.127 (0.167)	0.113 (0.162)	-0.076 (0.295)
Synchronous Revision Mechanism	0.037 (0.127)	0.175 (0.743)	0.048 (0.144)	0.188 (0.154)	-0.189 (0.254)
Revision Cheap Talk	0.039 (0.120)	0.250 (0.703)	0.114 (0.143)	0.044 (0.139)	0.100 (0.232)
Richer Revision Cheap Talk	0.047 (0.148)	0.325 (0.843)	0.156 (0.140)	0.088 (0.138)	0.084 (0.342)
Round	0.031*** (0.004)	0.178*** (0.024)	0.023*** (0.005)	0.047*** (0.006)	-0.097*** (0.012)
Constant	0.608*** (0.159)	3.630*** (0.623)	0.317*** (0.120)	0.018 (0.114)	0.952** (0.392)
Quiz	0.002 (0.019)				0.026 (0.037)
R ²	0.166	0.15	0.156	0.219	0.0866
Observations	5280	880	880	880	5280
Demographics	Yes	NA	NA	NA	Yes

Note: Standard errors clustered at the group level are in parentheses; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Reference category is standard cheap talk S-CT;

Payoffs variable is a subject payoff in a round. Minimum Effort, Freq Efficient Effort, Full Coordination are a group level measures and subject demographic information is not applicable. Eqbm Deviation is a subject level variable.

(a) Eqbm. deviation of revised efforts



(b) Average effort and full coordination

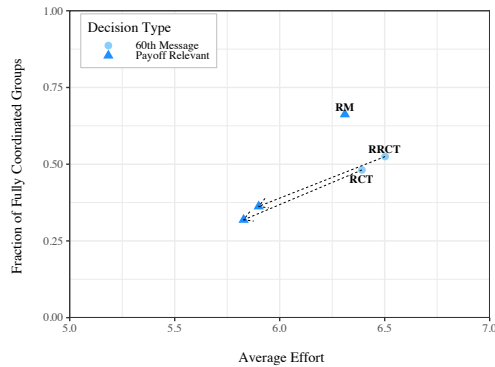


Figure 8: Equilibrium Deviation over Time

E.5 Dynamics over 60 seconds and 10 rounds

In this section we include some graphs highlighting subjects' behavior over 60 second pre-play phase (averaged over all 10 rounds). Then, we present the behavior over 10 rounds separately.

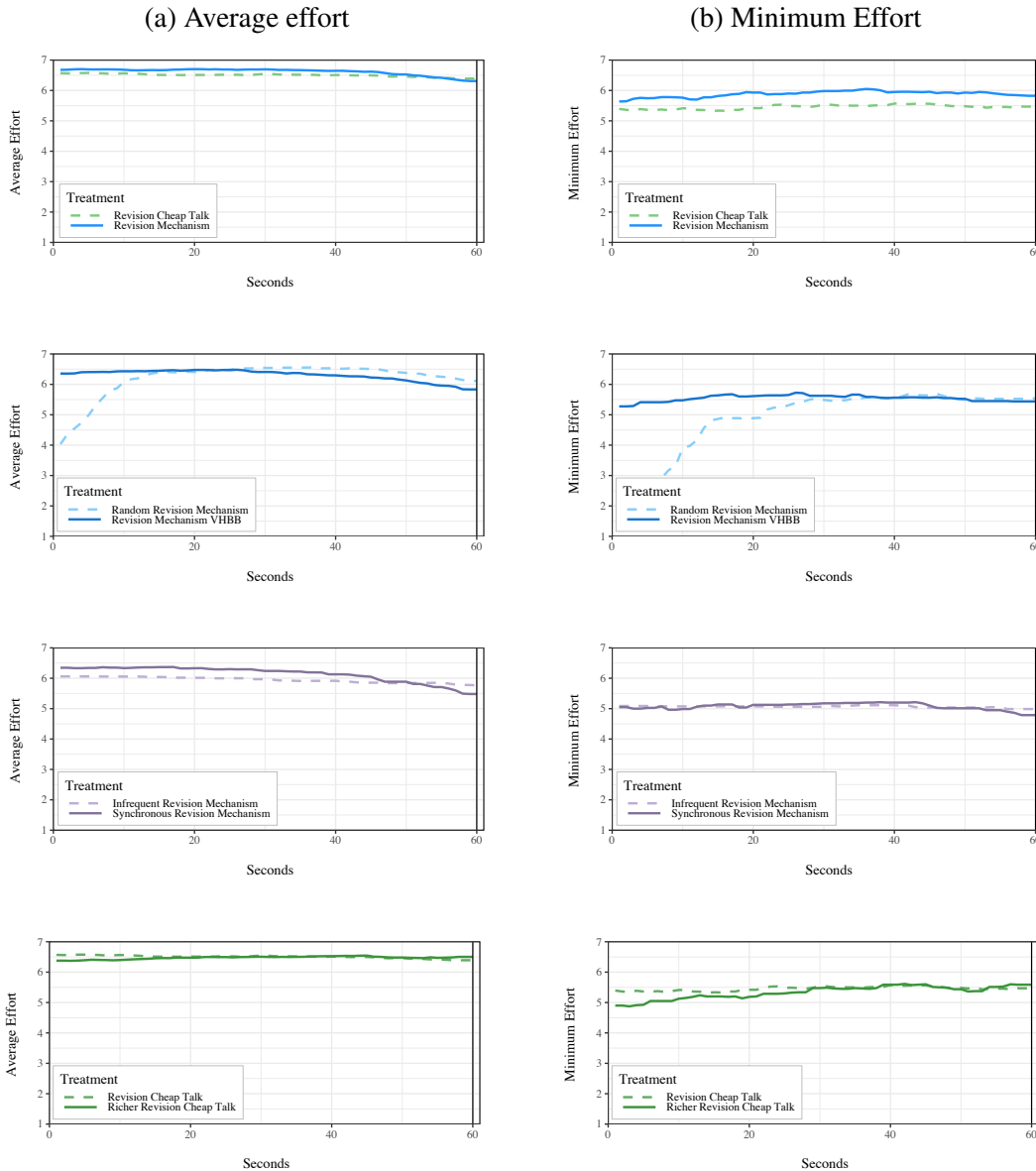
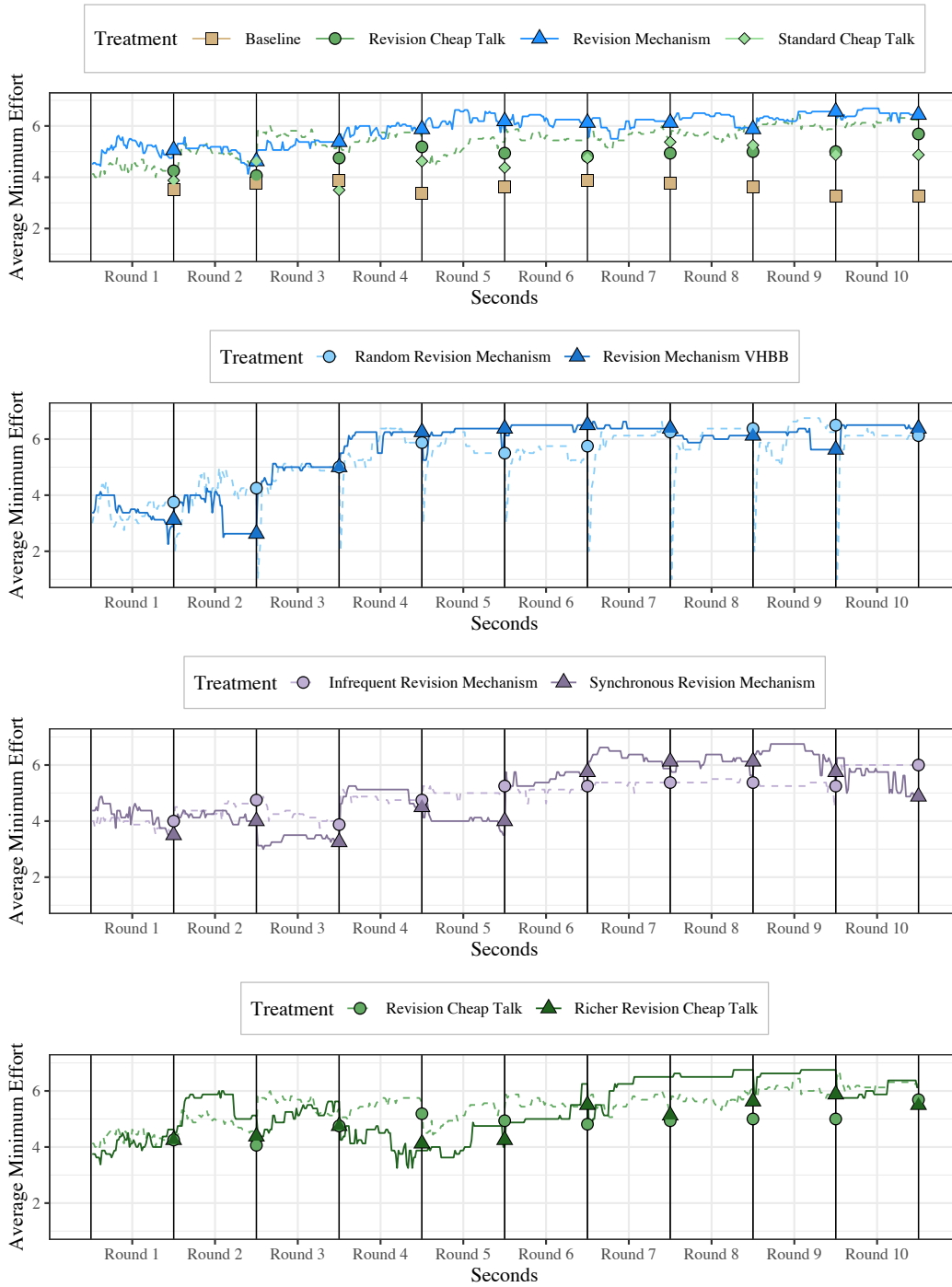


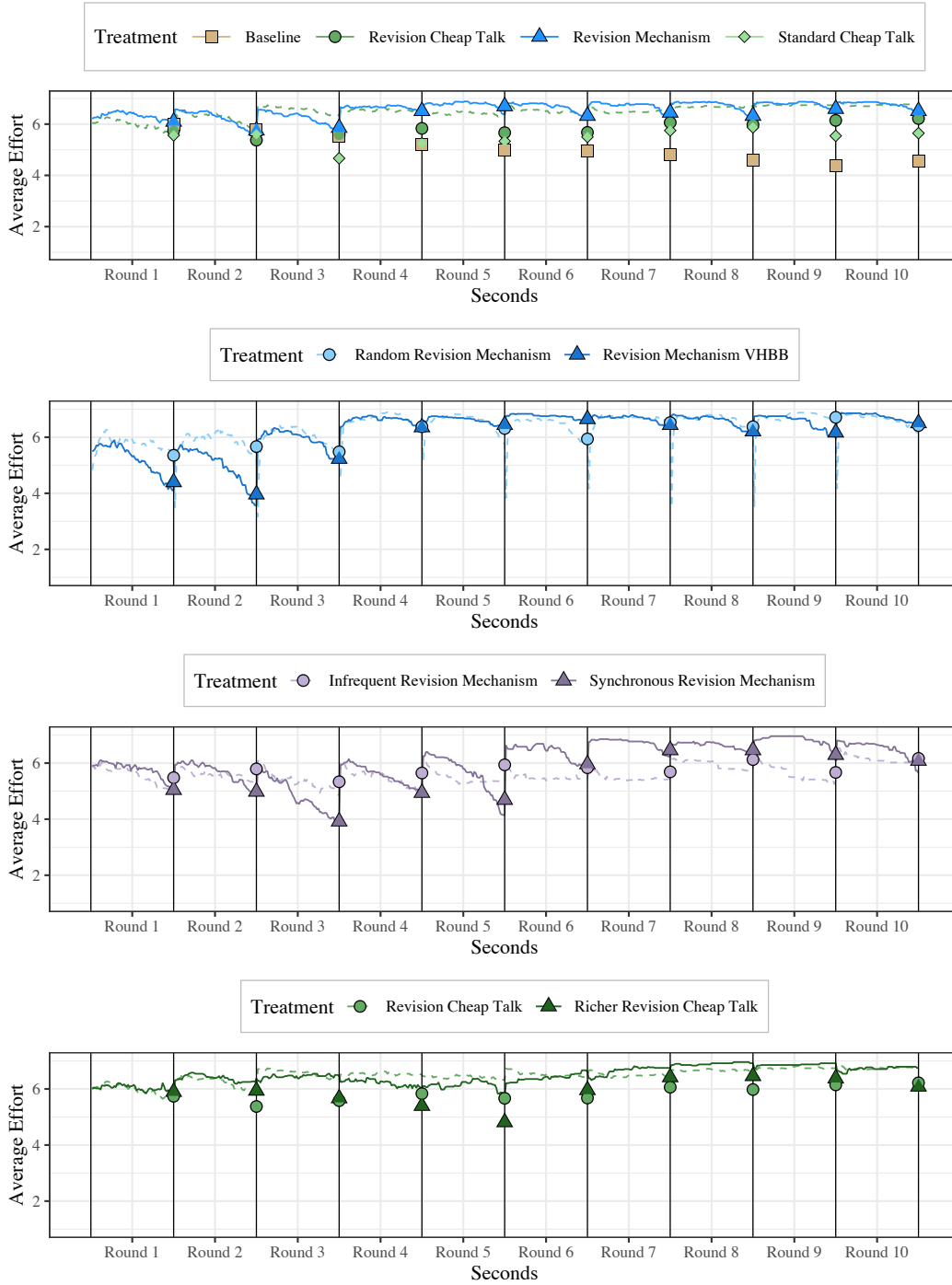
Figure 9: Average and minimum effort over 60 seconds

Figure 10: Average minimum effort over 60 seconds and 10 rounds



For **B**, **S-CT**, **R-CT**, and **R-R-CT**, the 60th second points on the graph represent the payoff relevant choices.

Figure 11: Average effort over 60 seconds and 10 rounds



For **B**, **S-CT**, **R-CT**, and **R-R-CT**, the 60th second points on the graph represent the payoff relevant choices.

E.6 I-RM vs RM—revised efforts, posted efforts, and initial choices

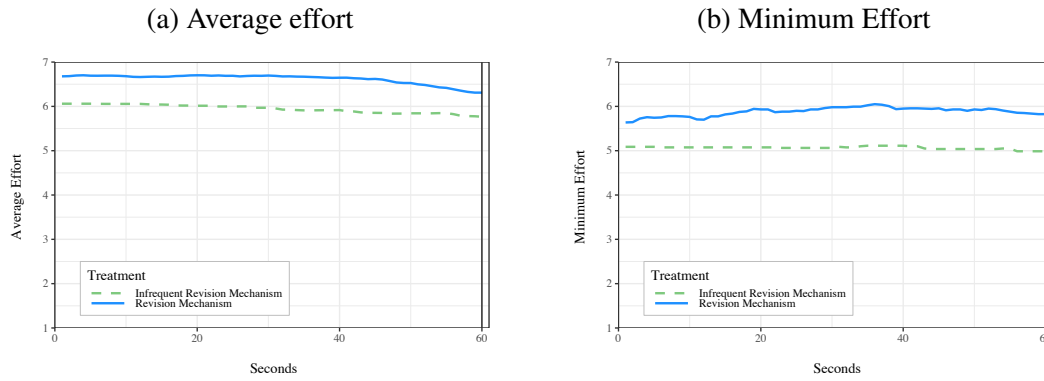


Figure 12: Average effort over 60 seconds

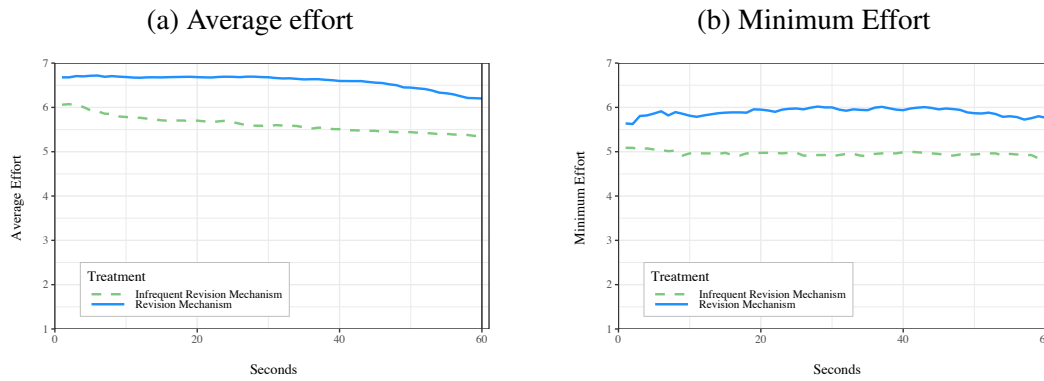


Figure 13: Average and minimum effort over 60 seconds (instant choice data)

<i>Treatment/Effort</i>	1	2	3	4	5	6	7
RM	1.3	0.7	0.4	1.6	4.4	5.9	85.7
I-RM	3.1	1.9	2.9	9.0	7.3	12.7	63.1

Table 11: Initial choice frequency distribution

F Revised effort vs posted effort

In our paper, actions can be changed only when a revision opportunity is awarded. Thus, in any instant, two different data points exist per player: (i) the effort the player is currently committed to, which all the other players are observing, and (ii) the effort currently selected by the player. Only after a revision opportunity is awarded can the selected effort choice become the effort to which the player is committed.

Let us evaluate the robustness of our experimental design by examining whether our choices of the time-interval length and the revision probability had an impact on the choices. We therefore compare the last-instant intended efforts with the efforts played out. If the time interval were too short or the revisions too infrequent, the players' intended actions would differ from the posted actions, even in the last instant, and subjects would have been constrained in their choice process. However, we cannot reject the hypothesis of equal distributions of actions ($p > 0.1$), which indicates the choice of interval length and revision frequency did not bind players' behaviors, thus aligning our experimental design with the conditions of the main proposition.